VESIENTUTKIMUSLAITOKSEN JULKAISUJA
PUBLICATIONS OF THE WATER RESEARCH INSTITUTE 32

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GROUND-WATER FLOW VELOCITY AS AN INDICATOR OF THE PERMEABILITY AND INTERNAL STRUCTURE OF ESKERS

Tiivistelmä

Pohjaveden virtausnopeus ja sen kuvastama harjujen vedenläpäisevyys ja sisäinen rakenne

VESIHALLITUS—NATIONAL BOARD OF WATERS, FINLAND
Helsinki 1979

ISBN 951-46-3951-0
ISSN 0355-0982

Helsinki 1979. Valtion painatuskeskus

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MÄLKKI, E. 1979. Ground-water flow velocity as an indicator of the permeability and internal structure of eskers. Publications of the Water Research Institute, National Board of Waters, Finland, No. 32.

A tracer dilution method based on colorimetry and an interpretation model taking into consideration hydraulic disturbances were developed. Longitudinal flow velocity and permeability vary between eskers in multiples of ten whereas individual values of flow velocity and permeability vary in hundreds. The hydraulic properties are studied here on the basis of the permeability of the formation. A generalized classification for the permeability of gravel-sand fractions is given. The ratio of gravel-sand aquifers in the basal portions of the eskers is 4/6, the structure is universally stratified and the material is well sorted. The length of the hydraulically uniform strata may exceed 10 km. The basal portion is assumed to have partly sedimented as a specific basal facies during the early glaciofluvial phase and reaches a distance of 10 km or more from the glacier margin.

Index words: tracer dilution method, point dilution method, ground-water, flow velocity, permeability, hydraulic gradient, esker structure.

1. INTRODUCTION

The general features of the laws governing ground-water flow have been known since the middle of the 19th century. In 1856 the Frenchman Henry Darcy presented the law named after him, which states that the flow velocity (v) of water in a porous medium is directly proportional to the permeability (k) of the medium and the hydraulic head (i), or (1)

$$v = ki \qquad (1)$$

Darcy's law has been used to calculate ground-water flows and has formed the basis of later mathematical development in this branch of research.

The flow conditions of water in the ground are well known in theory; however, as the flow occurs in geological strata of varying composition, thickness and depth, it is difficult to study the parameters needed for determining the flow velocity. First, it is difficult to obtain representative samples from the different parts of the geological formation concerned. Secondly, laboratory analysis seldom portrays correctly permeability in situ. Owing to variations in the permeability of the soil, problems related to ground-water flow in large areas can hardly be solved as in areally restricted technical surveys (Gustafsson 1968).

Under most geological conditions, flow velocities or movements in general of ground-water cannot be readily measured to give sufficiently representative results. In view of difficult conditions, the measuring methods used today are still very deficient. Most measurements consist of injecting a tracer substance into the ground-water flow field and tracing its deplacement with the ground-water (e.g. Knutsson 1970, Kinnunen 1978). As ground-water flow velocities are usually small, of the order of centimetres or metres per day, tracing is a time-consuming procedure. The possibility of tracing the injected substance may be limited by the structure of the formation and the difficulty of establishing observation points. The shorter the observation distance, the more limited is the esker cross-section represented. Owing to the limitations imposed by the measuring technique, the number of direct measurements of ground-water flow velocity in geological formations is very low. This is reflected in the hydrological and hydrogeological literature. Numerous works have been published on ground-water flow theory and measuring methods but very few on observation results on flow velocity itself.

In the last few decades a new measuring technique based on the dilution velocity of a tracer substance has been applied to determine ground-water flow velocity. To date only a few results have been published.

Ground-water movement offer an important means for studying geological structures and hydraulic properties in the soil below ground-water level. Measurement of ground-water movement gives a reliable picture of in situ geological conditions, e.g. in the basal portion of an esker.

The aims of the present study were, with dilution measurements,

1. to study the flow velocity of water in the longitudinal direction of the eskers in the central, usually most permeable, portions and the relevant hydraulic gradient;
2. to study the permeability of the soil using ground-water flow velocity as indicator; and
3. to obtain information on the composition of the basal portions of the formations and their internal structure with the aid of the movement of water and to draw some conclusions on the genesis of the eskers.

2. THE RESEARCH METHOD AND PROCEDURE

2.1 The research method

2.11 The tracer dilution method

The ground-water flow velocities were determined by tracer dilution, a technique whereby ground-water flow velocity is measured from a borehole or filter tube in which the tracer is diluted by ground-water flowing through the tube.

In the literature this method is known variously as the "single well method", the "borehole dilution method" and the "point dilution method". In this study, the term "tracer dilution method" is used and is suggested in replacement of the others for the following reasons:

1. The method is largely based on measuring the dilution velocity of the tracer. The term "tracer dilution" illustrates this and distinguishes it from numerous other types of measurements with a single tube, e.g. standard well-logging measurement.
2. A more advanced form of measuring requires observations in the environment as well (see Section 2.12).
3. The same technique can be applied to both ground-water and surface water.

The theory of the method has been described by many authors, e.g. Kocherin (1916, quoted by Ogilvi and Fedorovich), Ogilvi and Fedorovich (1966), Koch et al. (1967), Halevy (1968), Carlsson (1969, 1970 a, b), Gaspar and Oncescu (1972), Moser (1972) and Mälkki (1978 a, b).

Although the theory of the method has been known since 1916 (Ogilvi and Fedorovich 1966), it has been difficult to apply it for a number of reasons, e.g. the demands on instrumentation and measuring techniques related to small tube diameters. As late as 1968, Halevy mentioned that measuring instruments meeting certain essential requirements are either laboratory prototypes or operate at small depth ranges only.

For lack of efficient instruments and a suitable isotope technique, and with the measurement of very small velocities (< 1 m/d) as a starting point, a measuring device based on colorimetry was developed at the outset of this study in 1964. Its probe (Fig. 1) which can be inserted into the tube, consists of a chamber for the tracer, seals for insulating the measuring space in the tube and a ring-shaped stirrer that moves in a vertical direction. It also comprises a source of light and a photocell where the current is conducted from the surface of the ground. Once the tracer has been injected its dilution velocity is indicated by the rate of change in the current passing the photocell. This change is recorded by an instrument on the surface of the ground. Fig. 2 gives the relation between the current indicated by the instrument and the dilution ratio of the tracer. To remove turbidity and tracer residues from previous measurements from the tube the measuring device is provided with a flushing mechanism, which also improves the hydraulic operation of the tube.

A colloidal solution (carbon black) was used as tracer. According to Fick's law the number of molecules dn passing under the effect of diffusion through a cross-section area q in a certain time dt is proportional to the decrement of consentration, i.e. (2)

$$dn = -Dq \cdot \frac{dc}{dx} \cdot dt \qquad (2)$$

in which $-dc/dx$ is the decrease in concentration per unit length. It is well known that the coefficient of proportionality D, the diffusion coefficient, is approximately inversely proportional to the square root of the molecular weight of the diffusing substance, or, for spherical macromolecules, to the cubic root. The diffusion velocity can thus be reduced if the molar concentration of the tracer decreases with regard to water or if its molecular weight increases. When a macromolecular colloidal solution is used as tracer substance a small diffusion constant due to molecule size is obtained at the same time as a small diffusion velocity due to small molar concentration (Mälkki 1970a).

A colloidal solution is ideal, not only for its diffusion properties, but also with regard to density, as density can be adjusted to a value very similar to that of water. The factors that lead to errors arising from the density and diffusion properties of the tracer and from possible osmotic circulation are significant when actual velocities of less than 1 m/d are measured (Ogilvi and Fedorovich 1966 p. 14, Klotz 1969, Moser 1972).

A drawback to the colorimetric method is that it can only be used in waters of sufficient optical clarity. The aquifers studied represent ground-waters of this kind. The observation tubes should be well flushed to eliminate turbidity and to guarantee hydraulic functioning.

Most measuring instruments based on the dilution technique use radioisotopes (e.g. Halevy

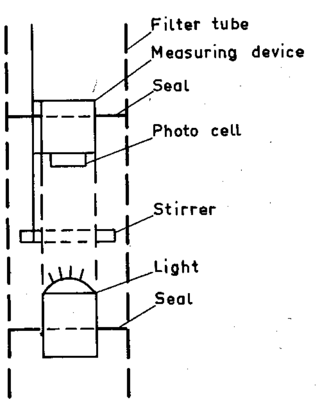

Fig. 1. Probe of measuring device in filter tube, schematic drawing.

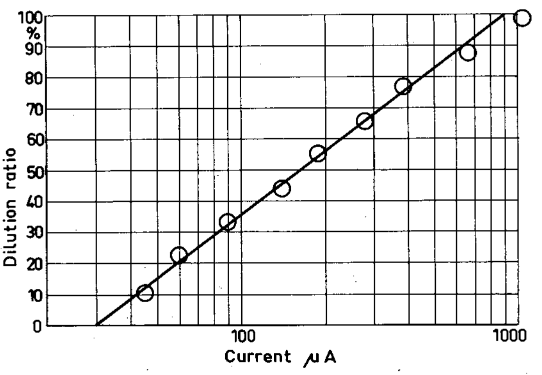

Fig. 2. Dependence of electrical current of measuring cell on dilution ratio of tracer.

1968 p. 141, Gaspar and Oncescu 1972, Peter and Hulla 1970); some use other tracers, mostly electrolyte solutions (Ogilvi and Fedorovich 1966, Carlsson 1969).

Provided that, irrespective of the technique, the measuring instruments meet certain basic requirements regarding measuring volume, output of results, insulation of the measuring space and mixing of the tracer, the instrumentation is not significant in studies on eskers as far as the measuring operation itself and the level of the results are concerned. The problem is the interpretation of the results, i.e. the conversion of the dilution velocity subject to hydraulic factors into the actual flow velocity (Mälkki 1978a). The problem is especially acute when the perforation degree of the tube is small, less than 8 per cent (Gaspar and Oncescu 1972 p. 119), and the vertical variation in the ratio of permeability of the measuring tube to that of its environment has a significant effect on the ratio of dilution velocity to flow velocity at different levels.

So far the ground-water flow velocity has generally been calculated from the equation (3)

$$v_f = -\frac{V}{\alpha \cdot F \cdot t} \ln \frac{C}{C_o} \qquad (3)$$

where

v_f = apparent flow velocity

V = measuring volume

F = greatest cross-section of the measuring space

t = time between concentrations C_o and C

α = proportionality coefficient giving the ratio of the volume of water flowing through the measuring tube to that flowing at the same time through an aquifer of the same width as the measuring tube (Fig. 3).

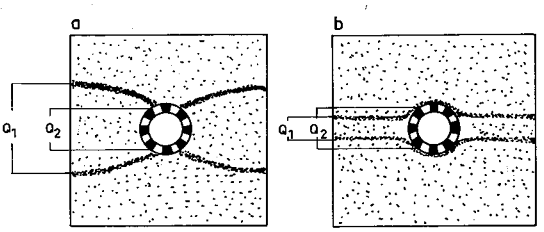

Fig. 3. Flow lines of ground-water distorted by filter tube: formation of coefficient α. a) $k_1 \cong k_2$, Q_1/Q_2 ($=\alpha$) $\cong 2$; b) $k_1 < k_2$, $Q_1/Q_2 \cong 0.5$. Q_1 = volume of water flowing through the filter tube; Q_2 = volume of water flowing at the same time through an aquifer of the same width as the filter tube. Parameters k_1 and k_2 see Fig. 4.

The relation between coefficient α and the parameters related to the measuring tube and the aquifer is given in Fig. 4. The coefficient α varies approximately between 0.1 and 2.3 depending on the ratio k_2/k_1. As the coefficient α changes rapidly when k_2/k_1 is between 1 and 30 (Fig. 4) its determination by estimation may cause a tenfold error. "The coefficient α is of great significance for an exact establishment of the seepage rate by the (electrolytic) method, but, in practice, it does not lend itself to a direct determination, since it is usually difficult to establish the permeability of the filter. A still more difficult problem is to show the presence and to estimate the water permeability of a crust of gravel on the walls of the borehole" (Ogilvi and Fedorovich 1966 p. 6).

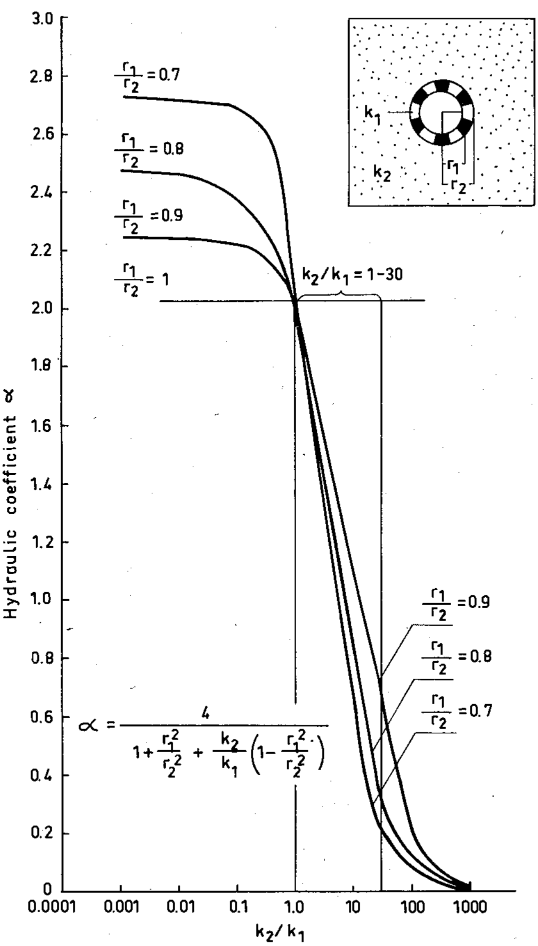

Fig. 4. Dependence of coefficient α on ratio k_2/k_1 and r_1/r_2.

2.12 Interpretation of results

To improve the accuracy of the results an interpretation model was developed that takes into consideration the hydraulic disturbances caused in the flow field by the tube, in accordance with geological conditions. The interpretation is based on knowledge of the hydraulic gradient at the measuring site and on empirical calibration, which, under practical conditions, has to be done separately for each type of filter tube and instrument. Empirical calibration of the instrument is called for because different devices have different effects when they are operating in the measuring space. In addition, the form and distribution of the perforations on the filter tube influence both the permeability properties of the tube and its hydraulic behaviour. The calibration was done in the flow velocity range 0—100 m/d in a 0.5 m^3 test basin using four filter sands of known grain size. Their permeabilities were determined (Table 7) at the beginning of the test. Two materials were chosen whose permeabilities were such that, considering the permeability of the filter tube, the k_2/k_1 -ratios fall in both the upper and lower parts of the change-sensitive interval of the α coefficients (Fig. 4). The k-values and k_2/k_1 ratios of these materials were as follows:

	grain size (mm)	k (m/s)	k_2/k_1
filter tube		$0.14 \cdot 10^{-2}$	
filter sand 1	0.5—1	$0.20 \cdot 10^{-2}$	1.43
filter sand 2	2—3	$2.0 \cdot 10^{-2}$	14.3

The tube (perforated area 4.7 %) inserted in the filter sand was flushed like the measuring tubes in the field. During calibration, when a series of flow velocities were measured, the following was observed:

1. An increase in light penetration through the liquid caused by dilution of the tracer in the measuring space and a corresponding change in the electric current in a time unit. A specific curve can then be drawn giving the angular coefficient b of dilution velocity for each measurement (Fig. 5).
2. The actual flow velocity on the basis of the water quantity flowing through a test basin mass of known porosity. An effective porosity value of 38 % was used for the test basin mass. This is approximately equivalent to the total porosity of filter sand 2 and the effective porosity (total porosity about 41 %) of filter sand 1.

The regression lines of the two test series were drawn (Fig. 6) on the basis of the angular coefficient of the curves representing the observed flow velocities.

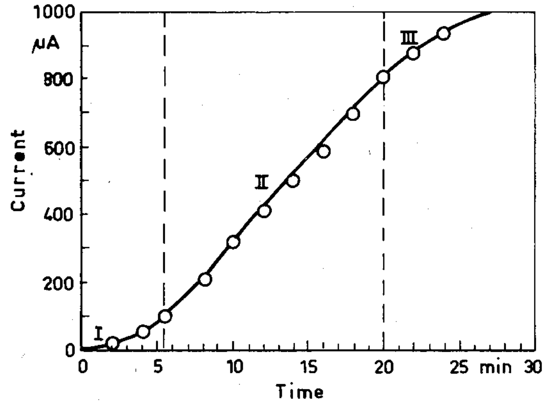

Fig. 5. Curve of tracer dilution velocity obtained by colorimetric method. I = initial part, partly distorted; II = optimum area of dilution process; III = high dilution ratio, not applicable end of curve. Adapted from Ogilvi and Fedorovich (1966).

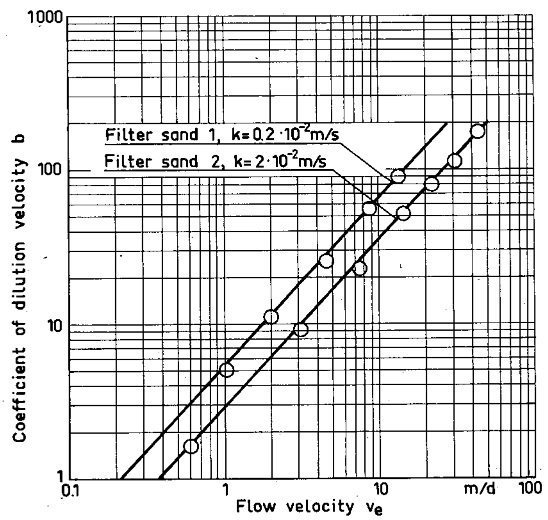

Fig. 6. Regression lines of angular coefficients of dilution velocities representing different flow velocities.

Using Darcy's equation (4)

$$v_e = \frac{k\,i}{n_e} \tag{4}$$

where
v_e = actual effective flow velocity
n_e = effective porosity of the filter sand

the hydraulic gradients were determined for different flow velocities.

The results were used to draw up a nomogram (Fig. 7) in which the abscissa is the actual flow velocity v_e, the ordinate is the angular coefficient of the dilution velocity b and the straight lines represent the values of the hydraulic gradient.

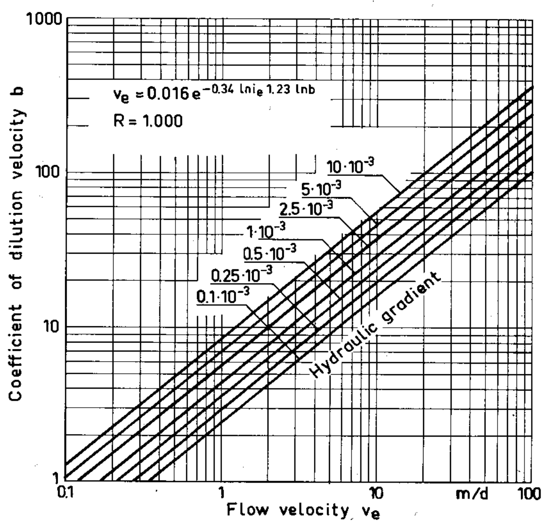

Fig. 7. An interpretation nomogram for ground-water flow velocity.

An interpretation model that would take all the different factors into consideration was developed with the aid of selective regression analysis which selected the best explanatory combination of the variations of the hydraulic gradient and of the angular coefficient b of the dilution velocity. The total number of variables and their combinations was sixteen. The following general equation (5) was obtained:

$$v_e = A \cdot e^{B \cdot \ln i_e C \cdot \ln b} \tag{5}$$

During calibration the following values were obtained for the constants:

A = 0.016
B = −0.34
C = 1.23

The model (5) explained 100 % of the variance of v_e (R = 1.000). This must be incidental or due to the small number of observations.

The actual ground-water flow velocity is determined from equation (5) or from the nomogram (Fig. 7) by finding the value on the abscissa corresponding to the intersection of the line representing the hydraulic gradient and the calculated angular coefficient b (ordinate) of the tracer dilution velocity. The corresponding k-value is obtained from Darcy's equation (4). The upper limit in interpreting the results is the velocity of 100 m/d; the lower limit is at 0.1 m/d.

The calibration is only valid for the tube and the measuring instrument for which it was intended. The interpretation nomogram based on calibration with only two filter sands is generalized.

2.13 Accuracy of results

As far as accuracy is concerned, the tracer dilution method and the interpretation of results discussed in this paper have the following advantages:

1. Factors causing errors due to diffusion of the tracer, differences in densities, or osmotic circulation are not present (Section 2.11).
2. The empirical calibration of the measuring instrument simulates the conditions prevailing in the measuring tubes.
3. The tracer dilution rate can be converted on the basis of actual geological conditions into ground-water flow velocity (Section 2.12).
4. With the aid of empirical calibration the tracer dilution method can also be used under non-laminar flow conditions.

With the present tracer dilution method, the only one of the known error factors (Halevy 1968 p. 141, Carlsson 1969 p. 19, Mälkki 1978 b) that remains is the vertical flow that may be present in the tubes. This factor is not generally encountered under the soil conditions considered here; nevertheless, it should not be neglected. A significant vertical flow may be noticed in careful interpretation of the results. Flow velocity variations in the tube in a vertical direction in the stratified soil of glaciofluvial formations indicate in practice the absence of significant vertical flow (see e.g. Fig. 16); on the other hand, constant tracer dilution velocities in a vertical soil profile tend to indicate the presence of vertical flow.

Other error factors are:

1. Compaction of strata at tube installation (whereby the measured flow velocity is smaller than the actual one).
2. Greater soil wash-out with regard to calibration conditions when flushing the tubes (the effect is the inverse of the former).

It was estimated from the observations that the accuracy of the results expressed as the mean of each measuring tube deviated from the actual value by ± 20 % at the most. Owing to the abnormally high error factor the result may locally deviate from the actual value by ± 50 %. The probability of the occurrence of such a result is estimated to be less than 10 % provided, however, that the vertical flows affecting the results are noted in the measuring operation and in the interpretation of the results, and are not included in the study.

According to Halevy (1968), the error factors that occur in measuring dilution have a cumulative effect on the dilution velocities. In the sand-gravel soils examined in this study the compaction of soil strata on the one hand and wash-out on the other have mutually opposite effects; vertical flow, however, when it occurs, has a positive effect increasing dilution velocities. On the whole, the investigation results tend to show a positive rather than a negative deviation from the actual value. This is taken into consideration in the overall review of the measuring results (Section 2.41).

The flow velocities measured represent absolute values within the limits of measuring accuracy, when the measuring cell is entirely in a homogeneous stratum. When the cell traverses different substrata the result obtained is a combination of flow velocities. Thus, the readings obtained depend on the length of the measuring cell and the instrument used; the longer the measuring cell, the closer the readings are to mean values.

To ensure that similar results are obtained when the measurement is repeated (1) the instruments must be of equal length, (2) they must be exactly at the same measuring depth, and the same measuring procedure must be applied, (3) the hydraulic gradient must be the same and (4) the results must be interpreted in like manner. Figure 8 gives the results of a repeated measurement.

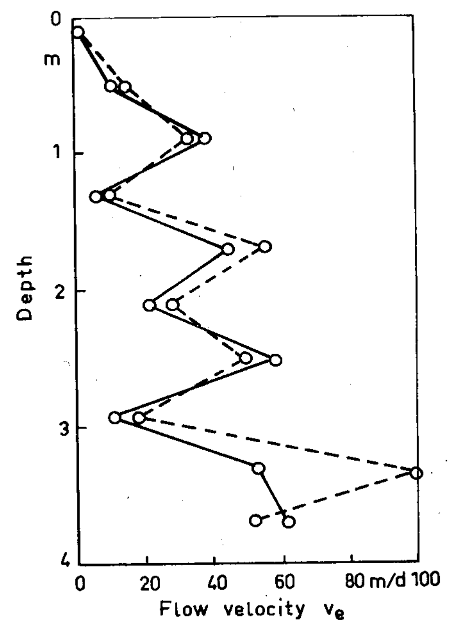

Fig. 8. Double flow velocity measurements in the same filter tube.

2.2 Selection of study areas and basic investigations

The most common types of radial glaciofluvial formations or eskers from the point of view of their geological structure and hydrogeological properties are those where the prevailing groundwater flow is parallel to the formation. The reasons for this, either combined or separately, are:

1. Eskers are usually formed in valleys (c.f. V. Okko 1975 p. 9, Virkkala 1948 p. 46, Flint 1971 p. 214, Banerjee and McDonald 1975 p.

134) and hence, the flanks of their basal portions are covered by poorly permeable sediments.

2. The longitudinal permeability of the formation may be more than tenfold that of lateral permeability (Winqvist and Marelius 1970).
3. The ground-water level in the esker may be lower than that of the surrounding area; thus outward lateral flow is hindered.
4. An esker area with good hydraulic connection may be more than a hundred times longer than it is wide.

Four such formations, where parallel flow is the dominant or sole component, were studied. In structure the formations vary from a narrow esker to a wide glaciofluvial delta. The study areas (communes in brackets) are:

- Koskenkorva (Ilmajoki)
- Kokkokangas (Isokyrö)
- Tullinkangas (Lammi)
- Lappakangas (Kuortane)

The study areas were chosen, mainly on the basis of the ground-water flow conditions described above, from some thirty areas investigated previously. Their ground-water flow velocities may be considered to represent characteristic flow velocities in different size categories although, if all such formations are considered as one group, the data handled are very limited (see also Section 2.5). The choice of the areas was also influenced by the hydrogeological data available mostly from previous studies. For the practical work the most suitable areas were those where the ground-water level is less than five metres below the surface.

The results of the geological soil survey were supplemented by unpublished data from earlier soil and ground-water investigations carried out for municipal water supply purposes in the Koskenkorva, Kokkokangas and Lappakangas areas. At Tullinkangas ground-water investigations have been the responsibility of the National Water Authority; unpublished soil survey results were also available from this area (M. Okko, oral communication 1975).

The data on these areas were studied. To examine the geological and hydrogeological conditions each area was submitted to air photo interpretation and field investigation. These observations, together with the earlier results, gave an overall picture of the geological structure of the area and the storage, flow and discharge of ground-water.

The concept "ground-water flow pattern" is used to give a general picture of ground-water flow conditions. In this study, the term synclinal flow pattern is used if the ground-water level is concave in a cross-section of the esker and its surroundings, and anticlinal if the ground-water level is convex (Mälkki 1970b).

In the text, elevations indicated with "plus" are elevations above sea level.

A geotechnical soil classification was used (Korhonen et al. 1974, see also Table 8).

2.3 Geological application of flow velocity measurements

Hundreds of different flow velocities can usually be measured in one cross-section of a glaciofluvial formation. The individual measuring points or lines must therefore be located carefully if representative results are to be obtained.

The following procedure was adopted to attain the objectives set for the study in Chapter 1.

1. The general geological structure and ground-water flow conditions were determined in each formation.
2. The principal flow zone of ground-water in the formation was determined or estimated. In the absence of accurate observations, the flow zone was presumed to be at the centre of the cross-section of the formation.
3. Single tubes were placed in the middle of the flow zone; series of several tubes were inserted into cross-sections across the effectively permeable zone.

2.4 The parameters to be determined

2.41 Ground-water flow velocity

The object of the study was to determine the actual ground-water flow velocity v_e, equation (4). The dimension of flow velocity is m/d.

According to geological and hydrogeological observations made in cross-sections of esker formations the soils vary from poorly permeable silts to highly permeable sands and gravels. Hence the range of variation in ground-water flow velocity in a cross-section may be considerable. The quantity of water flowing through the section in a time unit depends especially on the amount of soils of extreme grain size. It is thus advisable to omit some extreme values if the prevailing flow velocity in the esker is to be assessed.

In accordance with Section 2.13, the mean of the observation results statistically exceeds the actual value owing to error factors inherent in the method.

With these points in mind, the effective flow velocity of the formation was determined. Its magnitude is the arithmetic mean of individual measurements; this is obtained when 10 % of the minimum velocities (the extreme factor due to fine soil) and 20 % of the maximum velocities (the extreme factor due to extremely coarse soil and errors inherent in the method) are excluded. Hence values between 10 and 80 % are used.

The results obtained by the tracer dilution method should be considered primarily as local and referring to the point concerned. Provided that the conditions in the ground-water flow zone remain unchanged or that the variations can be interpreted – as usually happens in eskers – the results obtained by the tracer dilution method, even in a restricted area, may represent the flow velocity of a zone exceeding hundreds of metres, or even kilometres, in length. In such cases the results given by the method can be compared to those obtained by tracing ground-water flow with a tracer substance. The starting point in determining the magnitude of the effective flow velocity (see above) was that it should approximately correspond to the velocity of the water moving in the effective cross-section of the ground-water flow zone, which is also described by the tracing method.

The variation limits of the ground-water flow velocities, the mean values and the effective flow velocities referring to certain areas are given in Table 1. The distribution of the flow velocity into different categories is presented in Table 2.

Table 1. Variation limits and mean values of ground-water flow velocity; values of effective flow velocity.

Area	Number of observations	Ground-water flow velocity m/d: Variation limits v_e	Mean velocity*) v_e	Effective velocity V_e
Koskenkorva	113	1.5–>100	26.6	20.1
Kokkokangas	117	0.5–>100	19.9	13.5
Tullinkangas	45	1.2–>100	16.2	9.2
Lappakangas I	16	2.5– 39.1	11.0	8.7
Lappakangas II	7	19.4–>100	64.1	73.0
Lappakangas III	16	0.5– 18.7	4.3	2.9
All observations	314	0.5–>100	22.2	13.6

*) velocities $\leqq$ 100 m/d

2.42 Hydraulic gradient

The hydraulic gradient was determined parallel to the longitudinal direction of the formations studied; this is also the principal flow direction of the ground-water (Section 2.2). In interpreting the results the hydraulic gradient at the measuring site itself was used.

The variation limits and the weighted areal mean values of the hydraulic gradient are given in Table 3.

2.43 Soil permeability

The dimension of soil permeability (k) is m/s.

Table 2. Distribution (in per cent) of ground-water flow velocity in categories.

Area	Number of observations	Percentage of observations in the categories (m/d): $\leqq$2.5	>2.5–10	>10–25	>25–50	>50–100	>100	Total
Koskenkorva	113	3	23	27	13	16	18	100
Kokkokangas	117	13	31	25	14	12	5	100
Tullinkangas	45	11	46	22	6	11	4	100
Lappakangas I	16	-	50	44	6	-	-	100
Lappakangas II	7	-	-	14	14	58	14	100
Lappakangas III	16	38	56	6	-	-	-	100
All observations	314	9	32	25	12	13	9	100

Table 3. Variation limits and weighted mean values of hydraulic gradient by areas.

Area	Number of observations	Hydraulic gradient (10^{-3})	
		Variation limits	Weighted mean value
Koskenkorva	3	0.15–0.42	0.3
Kokkokangas	4	1.0 –3.0	1.2
Tullinkangas	3*)	0.4 –3.0	1.2
Lappakangas I	2	6.0	6.0
Lappakangas II	2	1.0	1.0
Lappakangas III	2	0.4 –1.0	0.24
All observations	16	0.15–6.0	1.3

*) observations between points 1–9

Table 4. Variation limits, mean values and indexes of soil permeability.

Area	Number of observations	Soil permeability (10^{-2}) m/s		
		Variation limits*) k	Mean value*) k	Permeability index K_e
Koskenkorva	113	0.7–43.9	11.7	11.9
Kokkokangas	117	0.1–18.1	3.6	2.5
Tullinkangas	45	0.2–20.0	3.3	2.4
Lappakangas I	16	0.3– 4.3	1.2	0.9
Lappakangas II	7	5.6–29.0	18.6	21.3
Lappakangas III	16	0.2–10.0	2.3	1.6
All observations	314	0.1–43.9	6.0	3.4

*)velocities $\lesseqqgtr$ 100 m/d

As with the effective flow velocity given in Section 2.41, the corresponding effective permeability of the formation – later called permeability index K_e – was determined from individual permeability observations (mean of permeabilities 10–80 %). The permeability index illustrates the longitudinal hydraulic properties of the esker in the zone of effective ground-water flow and may also be called the index of effective hydraulic conductivity. It is used to compare the permeability conditions of the formations studied with those of other areas.

Areal variation limits, mean values of permeability and permeability indexes are given in Table 4. The distribution of the permeability into size categories is given in Table 5.

2.5 Other data

Observations on ground-water flow velocity and hydraulic gradient were available for comparison from six areas (eskers). Geologically and hydrogeologically the eskers correspond to those studied, in the following aspects:

1. In dimension the eskers are of the same order of magnitude and, as in the study areas, of various widths.
2. The principal directions of ground-water flow – the longitudinal direction of the esker – are as in the study areas.
3. The longitudinal flow velocity and permeability of the formations vary.

The areas for comparison (communes in brackets) are:

- Kolpene (Rovaniemi)
- Hanhikemppi (Lappeenranta)
- Pässinlukot (Hausjärvi)
- Hiisimäki (Leppävirta)
- Jälänniemi (Siilinjärvi)
- Linnamäki (Porvoo)

The locations of the areas are shown in Fig. 9.

Table 5. Distribution (in per cent) of soil permeability in categories.

Area	Number of observations	Percentage of observations in the categories (m/s)					
		10^{-3}– $5\cdot10^{-3}$	$>5\cdot10^{-3}$– 10^{-2}	$>10^{-2}$– $5\cdot10^{-2}$	$>5\cdot10^{-2}$– $10\cdot10^{-2}$	$>10\cdot10^{-2}$	Total
Koskenkorva	113	-	3	26	21	50	100
Kokkokangas	117	17	10	44	13	16	100
Tullinkangas	45	14	16	45	7	18	100
Lappakangas I	16	19	25	56	-	-	100
Lappakangas II	7	-	-	-	14	86	100
Lappakangas III	16	13	6	69	6	6	100
All observations	314	10	9	39	14	28	100

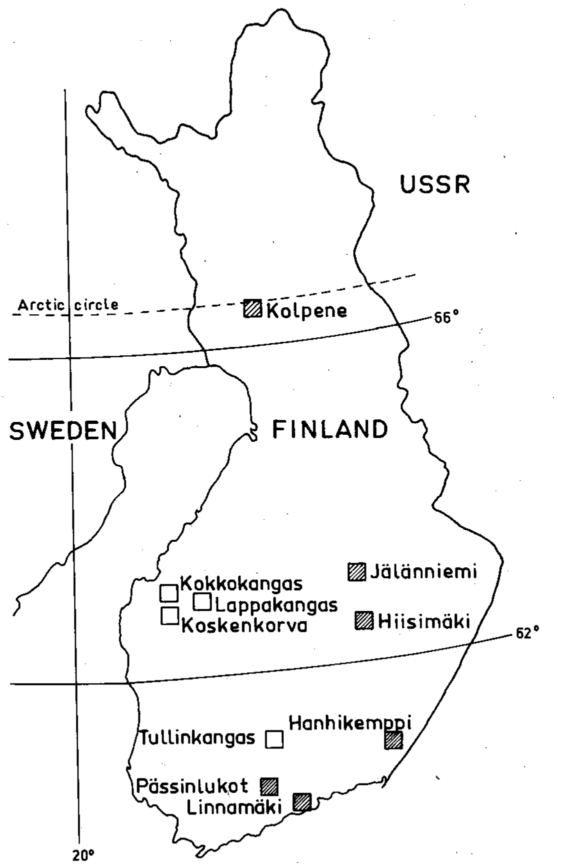

Fig. 9. Location of investigation areas. ▨ = study areas, □ = comparison areas.

The results of hundreds of individual ground-water investigations on eskers were also used (unpublished reports by Soil and Water Ltd and by the National Board of Waters). The personal experience that the author gained during these investigations was of great help in the geological and hydrogeological interpretations of the present study.

3. THE STUDY AREAS AND THE OBSERVATIONS

3.1 Koskenkorva

3.11 General geological features

The esker formation studied is part of a discontinuous and mainly narrow chain of eskers that starts at the Kyrönjoki river valley and as a fairly coherent zone, continues northwestwards for some 30 kms through the communes of Ilmajoki and Laihia. The esker divides into two branches north of the Koskenkorva area. The position of the study area in the esker system is presented in Fig. 10.

The Koskenkorva esker (Fig. 11) is located in a level-surfaced valley area filled with fine sediments. The dominant land elevation is +50—55 m. Some 1 to 2 km westwards the valley is bordered by a rock ridge rising + 100 m above sea level. Eastwards the margin of the valley cannot be determined.

The bedrock is mica gneiss (Laitakari 1942). In the study area there is a depression in the rock surface, whose level at Koskuslähde (spring area, the main part of the study area) is below +25 m. From the valley basin towards the western edge elevation differences of 60 to 80 m in the rock surface indicate a deeply eroded fault zone in the bedrock.

Drilling in the immediate vicinity of Koskuslähde has revealed that the soil layer is 30 m thick. A narrow string-like esker oriented SE-NW has formed on the deeply furrowed bedrock. The flanks and top of the esker are covered by a sequence of clay and silt sediment, which forms vast uniform planes, especially in the lowlying parts of the area (Mölder and Salmi 1954).

With the exception of some small hills, which constitute the narrow ridge badly broken by gravel pits, the esker rises only a few metres from the bottom of the valley. Drilling shows that the dominant soil types in the esker are gravelly sand and sandy gravel. The information given by the drilling about the different soil layers and their variations is, however, no more than directive.

3.12 Ground-water storage and the flow pattern

The discharge points at Koskuslähde are in the lowest part of the esker flank at the + 49 m level. The discharge level of the ground-water regulates the ground-water level in the area. As the bedrock surface at Koskuslähde is below the + 25 m level, the thickness of the aquifer is at least 24 m.

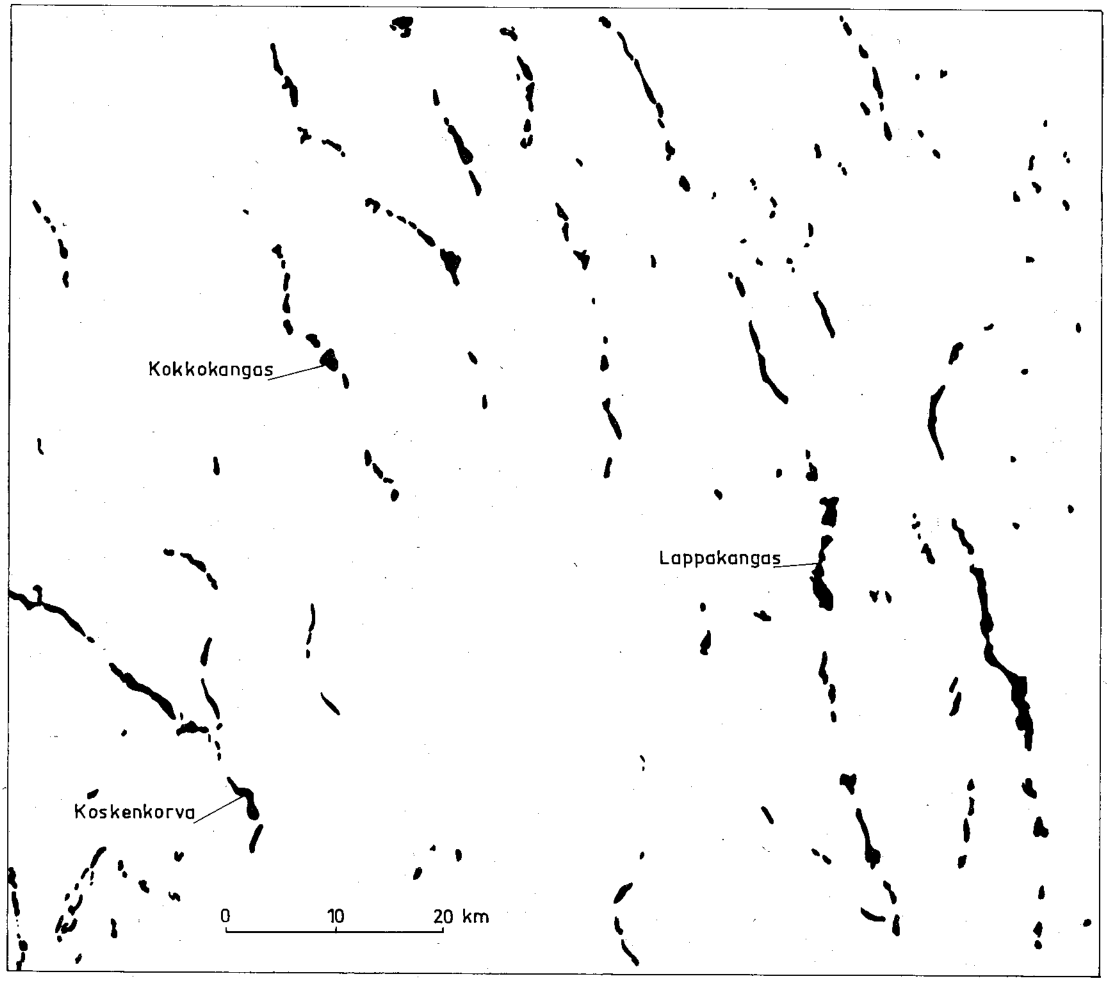

Fig. 10. The Koskenkorva, Kokkokangas and Lappakangas as part of the esker system.

The ground-water level, measured from wells, tubes and pits, inclines towards the springs over a distance of five kilometres from the northwest and three kilometres from the south.

The hydraulic gradient in the longitudinal direction of the esker varies in the range $0.15 \cdot 10^{-3}$–$0.42 \cdot 10^{-3}$ (Fig. 12). The elevation of the surrounding terrain and the few observations made on the ground-water level indicate, that the ground-water level inclines towards the esker, the gradient being about $3 \cdot 10^{-3}$–$5 \cdot 10^{-3}$. Thus the esker resembles a subsurface drain collecting water from its surroundings, with a synclinal flow pattern (Mälkki 1970b, see also Fig. 11).

This flow pattern indicates that large amounts of water flow and discharge through the esker in relation to the size of the formation. The survey performed by the National Board of Agriculture in 1967 showed that the minimum flow of the Koskuslähde area is about 4 500 m^3/d, although the recharge area itself is only roughly 1 km^2 (c.f. von Brömssen 1968, Lemmelä 1976).

3.13 Investigation results

Altogether 113 flow velocity measurements were made from tubes installed at points 3, 4, 5 and 6 (Fig. 11). The results are given in Fig. 13 and together with the results of the other areas in Tables

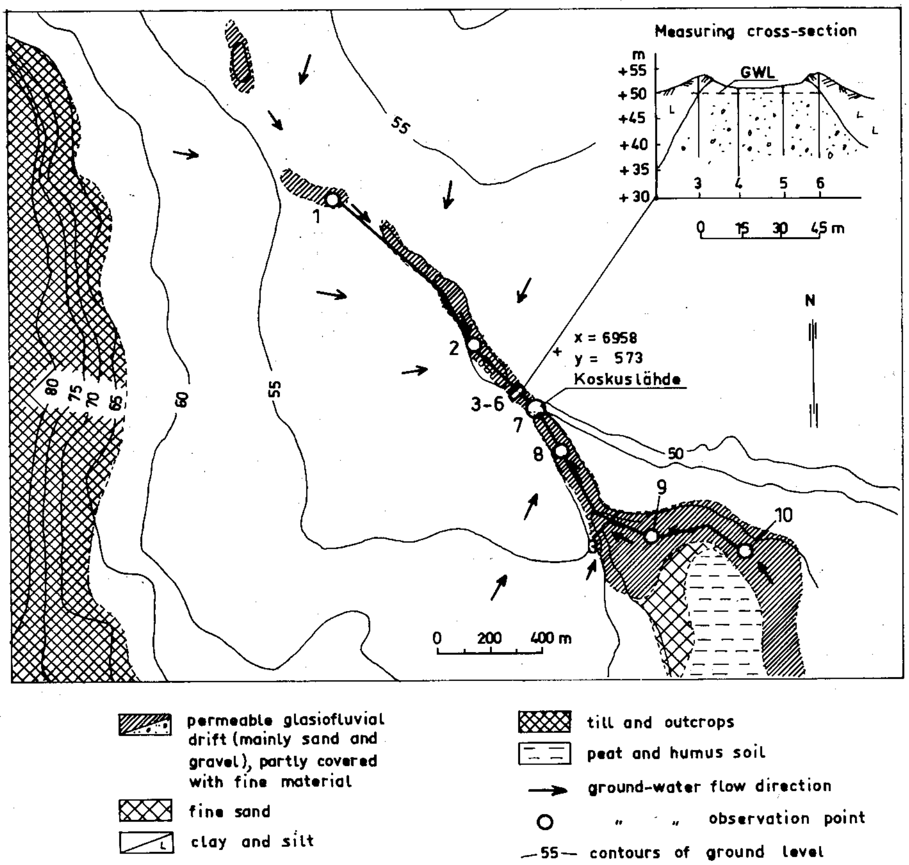

Fig. 11. Hydrogeological map of the Koskenkorva area.

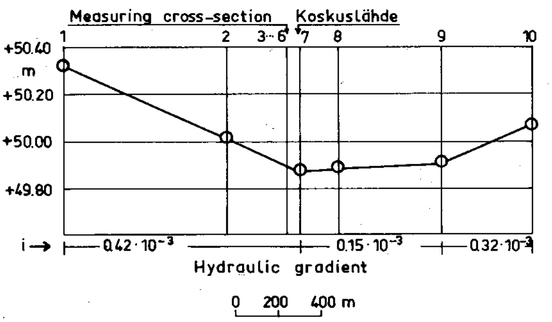

Fig. 12. Longitudinal section of ground-water level at Koskenkorva.

1 and 2. The interpretation limit of 100 m/d was exceeded by 18 % of the investigation results.

The variation in flow velocity was considerable in both vertical and horizontal direction. At a depth of 1—5 m below the ground-water level, flow velocities of the same order of magnitude were measured in all tubes; this indicates the presence of a homogeneous aquifer in the horizon. Below this horizon the flow velocity varies irregularly.

The permeability of the soil was calculated using the value $1 \cdot 10^{-3}$ of the hydraulic gradient. This is roughly 2.5 times greater than the longitudinal hydraulic gradient of the esker measured at that point and has brought about the greater lateral ground-water gradient. The variation in flow velocity presented above also describes the variations in permeability in the cross-section measured (see also Tables 4 and 5).

3.2 Kokkokangas

3.21 General geological features

Kokkokangas is part of a discontinuous esker chain southeast and northwest of Kokkokangas (Fig. 10). It is larger than the other parts of the esker and its soil is well sorted.

The terrain in and around Kokkokangas is

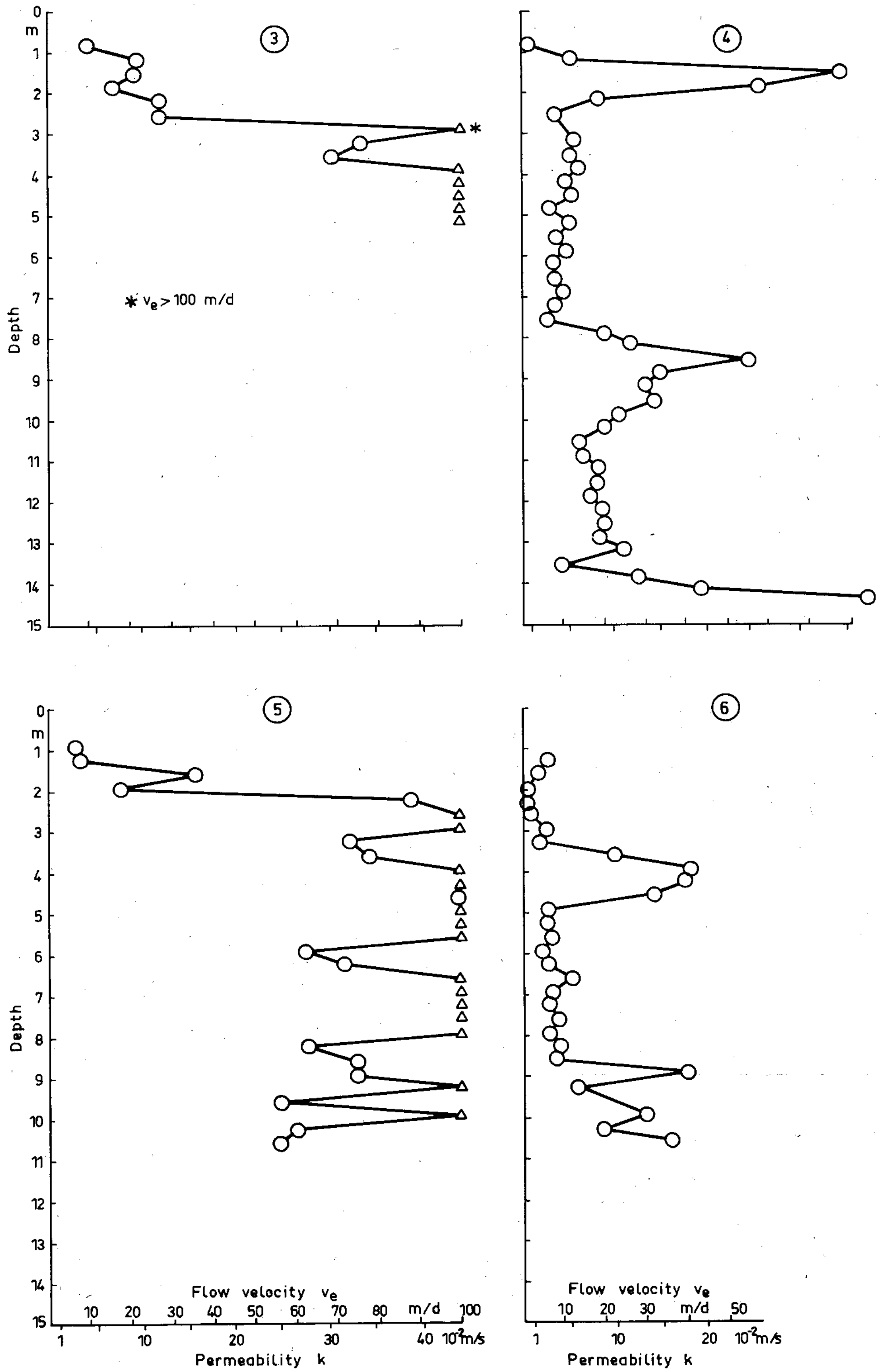

Fig. 13. Ground-water flow velocity and soil permeability at Koskenkorva. 0 m depth = ground-water level.

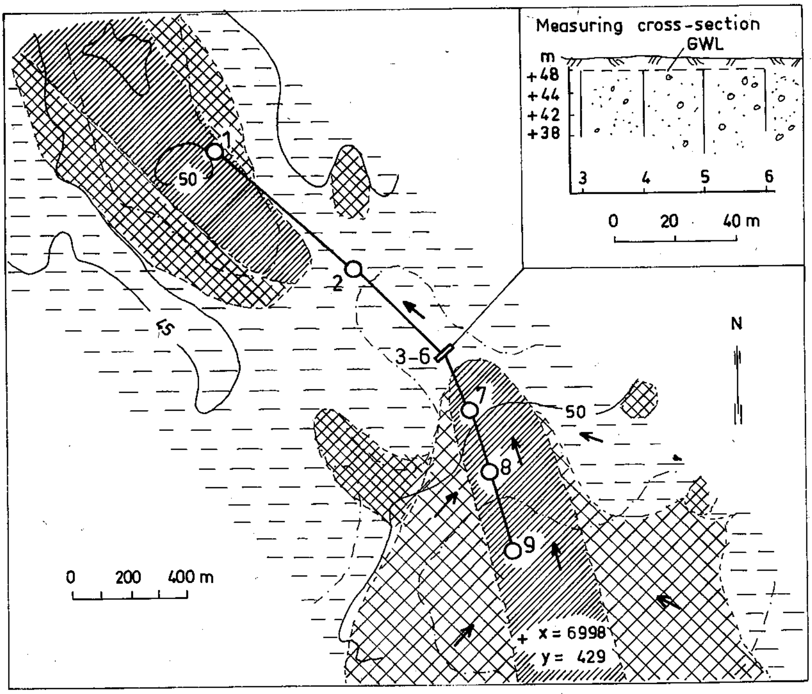

Fig. 14. Hydrogeological map of Kokkokangas. Legend, see Fig. 11.

very flat the dominant elevation being + 50 m (Fig. 14). Rock and till protrusions up to + 55 m cause local variation in topography and indicate on the map weak north-northwest orientation on either side of the glaciofluvial zone.

The bedrock is gneiss-granite (Laitakari 1942). Drilling and underwater gravel pits in the centre of Kokkokangas show that the bedrock is partly below the + 30 m level. The bedrock elevations on the flanks of the esker indicate below the glaciofluvial formation the presence of a parallel depression caused by a fault in the bedrock and erosion in the fault zone.

Gravel pits and drilling show that the southern part of Kokkokangas consists of fine sand and silt. In the central part of Kokkokangas there is a gravel-pit zone measuring 0.1-0.7 km^2 in which the dominant soil types are sand and gravelly sand. Stones and boulders occur occasionally, which is characteristic of this particular reach. Covered by organic sediments, the formation continues northwards towards Sarvikangas which is part of the same reach. The formation is 0.1 km wide at the site where the flow velocity was measured.

The middle and southern parts of Kokkokangas are geologically a glaciofluvial delta. The northern part is a levelled-out esker. The margins and the southern half of the area are mainly fine grained soils. Abrasion has smoothed the original surface structures and spread sand strata out beyond the original esker and delta areas.

3.22 Ground-water storage and the flow pattern

Owing to the height and flatness of the terrain surrounding the Kokkokangas area, the ground-water is stored in a subsurface layer 15–20 m thick. The thickness of the ground-water layer at the margins of the delta is unknown. The dominant ground-water level measured from pits and tubes in the centre of Kokkokangas is + 49 m, from where it inclines to the north-west (Fig. 15). At the cross-section studied, the hydraulic gradient is $2.4 \cdot 10^{-3}$. In the southern part of Kokkokangas the ground-water level inclines to the south.

The coarse-grained centre of the esker, into which ground-water flows from the margins of

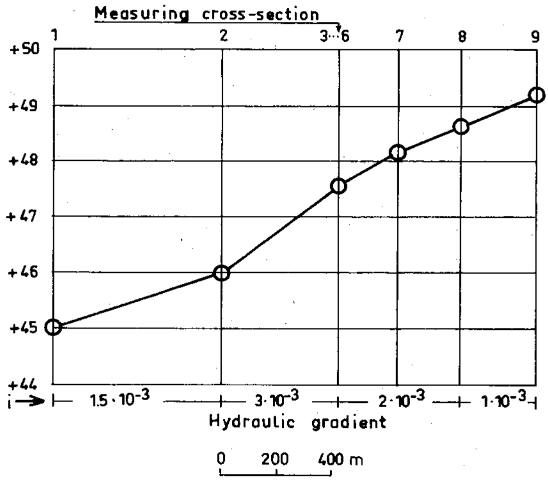

Fig. 15. Longitudinal section of ground-water level at Kokkokangas.

the formation as well, forms the principal zone of ground-water flow. Thus the ground-water flow pattern is synclinal.

3.23 Investigation results

Ground-water flow velocities were measured at points 3, 4, 5 and 6 in the cross-section studied (Fig. 14); that is, a total of 117 measurements. Of these 5 % exceeded the interpretation limit 100 m/d. The results are presented graphically in Fig. 16.

In tubes 3 and 4 the flow velocities were mostly less than 10 m/d. The dominant flow in the cross-section studied was around tubes 5 and 6 where the velocities measured exceeded 15 m/d except for the surface part and some individual strata. The flow velocity varied stratawise. The relative variations in the permeability of the soil are revealed by the flow velocity variations.

3.3 Tullinkangas

3.31 General geological features

Tullinkangas is part of an esker chain whose small separate formations reach southeast all the way to the First Salpausselkä ridge. Northwards the esker chain is larger and more coherent than towards the south and southeast (Fig. 17).

The Tullinkangas area is a delta oriented mainly E–W in which the variations in elevation are of the order of some metres only. The prevalent elevation is + 160 m. Tullinkangas is bordered in the west by the steep-shored Lake Selkäjärvi and in the east, where the terrain is slightly sloping, by the bog Halmansuo. In the north and south the area is bounded by rock and till ridges rising in these directions (Fig. 18).

The bedrock is mica-gneiss (Laitakari 1964). With the exception of the steep-walled outcrops in the northern part of the area the elevation of the bedrock is not known; thus, the thickness of the soil strata is also unknown.

In the western part of the delta the surface soil is pebble gravel and sand which is partly poorly and partly well sorted. Eastwards, the surface soil is sand and silt. North and south of the delta the soil is silt.

According to drilling, well-sorted coarse-grained soils (gravel and sand) are found along the entire length of Tullinkangas in a 0.5 km wide zone that varies in depth from a few metres to ten metres. Drilling done before the installation of the observation tubes reached this level at the most. Many of the intermediate strata are fine sand and silt.

South of Tullinkangas, in the middle of a flat sediment area, the esker ridge protrudes in places. The esker is partly steep sloped (inclination 40–50°) and at the top only some 5–15 m wide. The surface is stony, partly tilly gravel and sand with some boulder-rich areas. Distinctly outlined the esker continues through Selkäjärvi to the west-northwest.

3.32 Ground-water storage and the flow pattern

The ground-water is stored in an even layer that conforms with the ground surface. From the known thickness of the soil layer the ground-water layer has been estimated to be at least 6–8 m thick.

The ground-water level, measured from observation tubes, is inclined eastwards from Selkäjärvi. The gradient grows slowly at first but in the area of the bog Halmansuo, where the ground-water is discharged, the hydraulic gradient

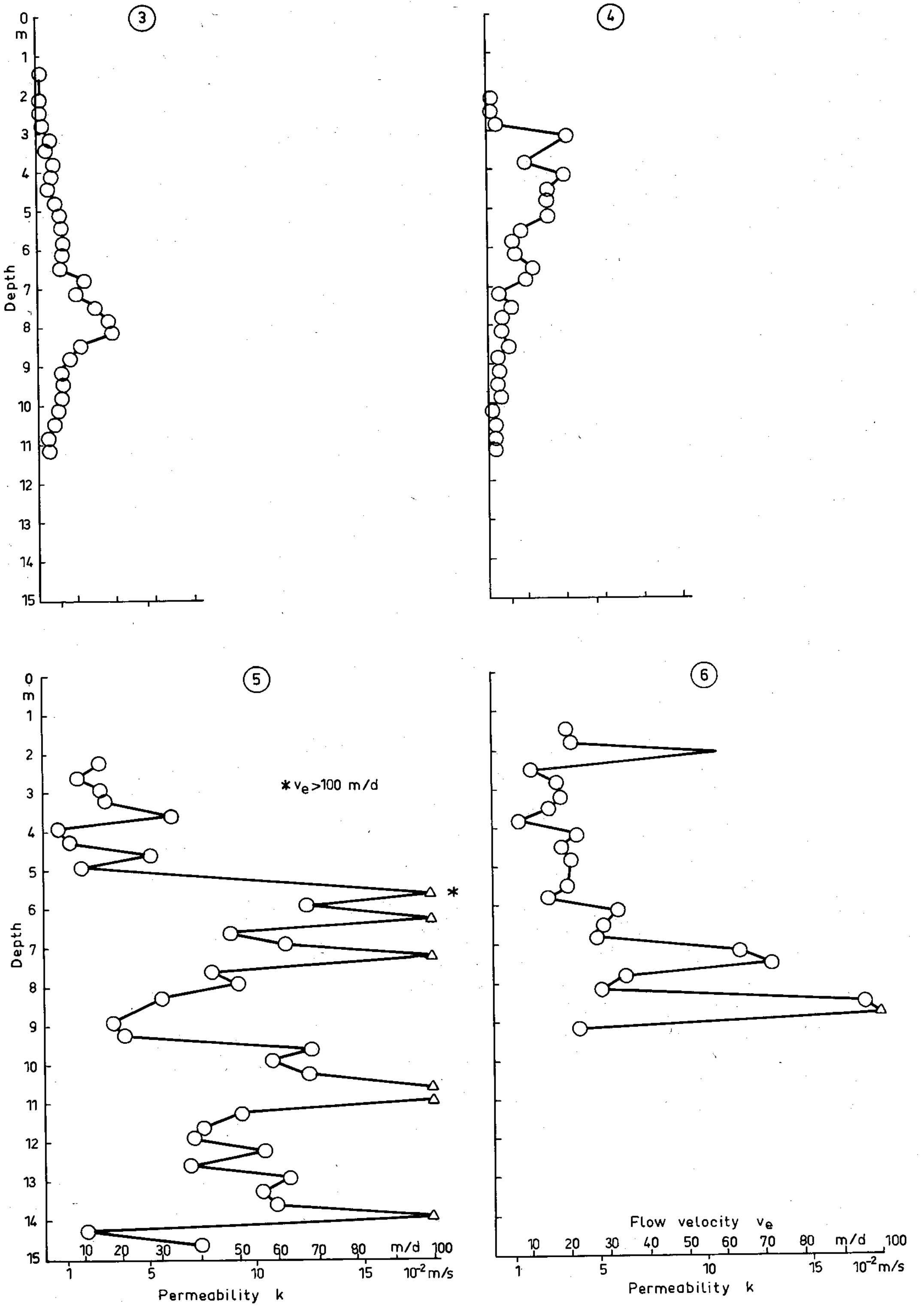

Fig. 16. Ground-water flow velocity and soil permeability at Kokkokangas. 0 m depth = ground-water level.

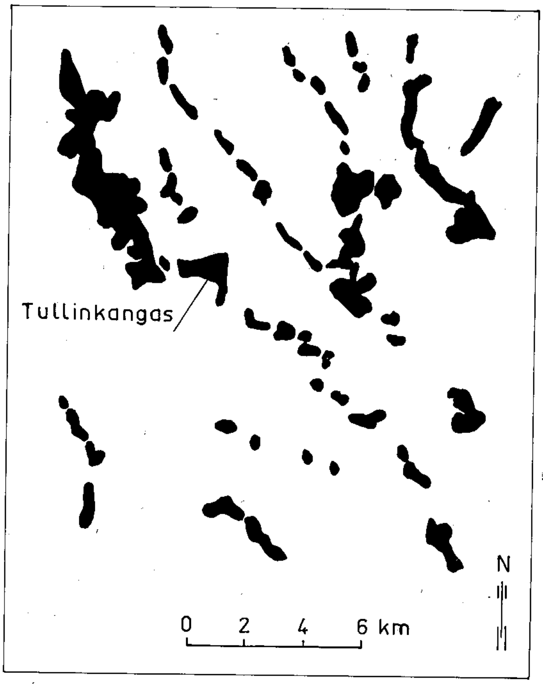

Fig. 17. Tullinkangas as part of the esker system.

increases rapidly (Fig. 19). Selkäjärvi has no outlets. Its water level is the same as the ground-water level on the shore of the lake. Water from the lake seeps into Tullinkangas and the level of water in the lake regulates that of ground-water in the Tullinkangas area. It can be deduced from the topography of the area and from observations made in the field that there is both surface and ground-water runoff into Tullinkangas from the peripheral areas of the delta. Hence the flow pattern of Tullinkangas resembles that of a synclinal esker. The main flow directions of the ground-water are given in Fig. 18.

3.33 Investigation results

Observations on ground-water flow velocity (Fig. 20) were made on line crossing the delta in tubes 4, 5, 6, 7 and 8. A total of 45 measurements was made. Of these 4 % exceeded the interpretation limit. Ground-water flow in the measuring horizon is most intense in the area of tubes 6–8, the observed maxima being around tube 8. The permeability of the soil complies with the above variations.

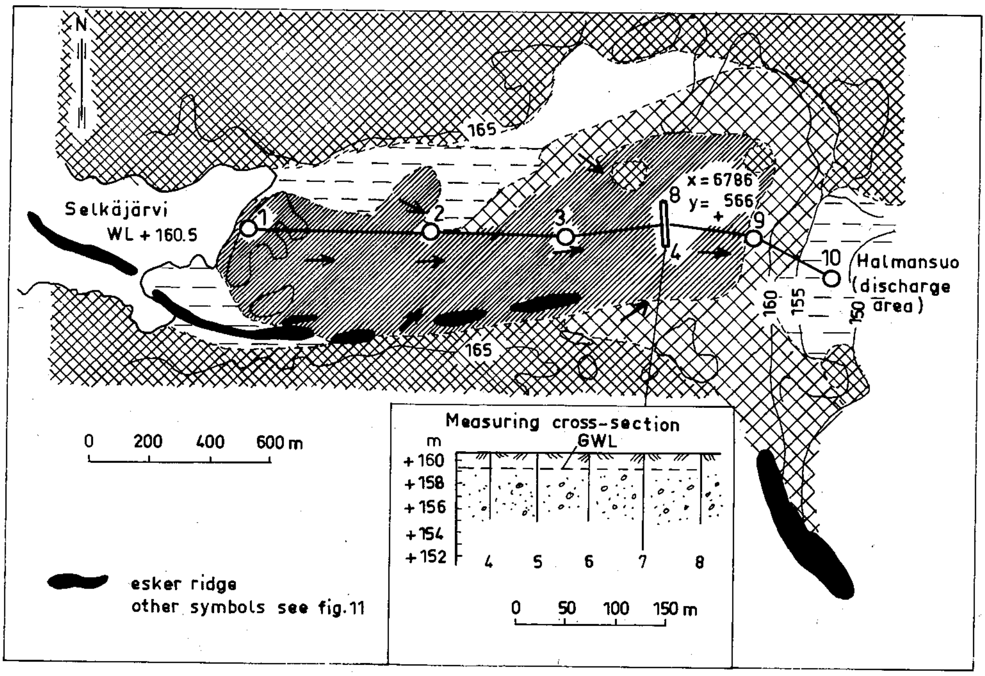

Fig. 18. Hydrogeological map of Tullinkangas. Legend, see Fig. 11.

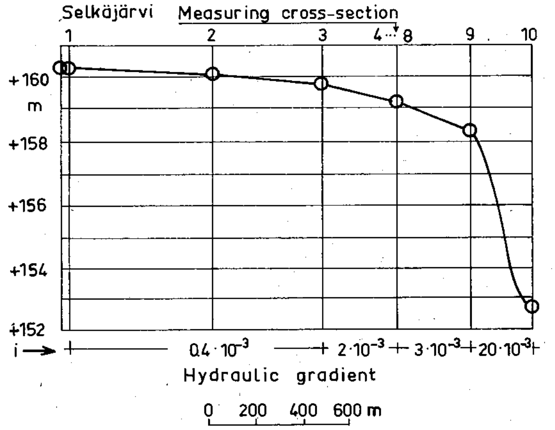

Fig. 19. Longitudinal section of ground-water level at Tullinkangas.

3.4 Lappakangas

3.41 General geological features

Lappakangas is part of a discontinuous esker chain (Fig. 10) over 100 km in length and oriented north to south. The base in the area is bedrock composed of mica-gneiss and mica-schist (Laitakari 1942, Tyrväinen 1971).

The total length of the Lappakangas esker formation is 7 km. Its southern part is a dilatation consisting mostly of coarse-grained gravel and sand that are partly well and partly poorly sorted. As far as is known, the formation is cut by a fault oriented SSW–NNE and the topographically high terrain behind it. In the course of this study, observations were made in the northern half of the area, which was divided into three subareas in the longitudinal direction of the formation (Fig. 21).

The first subarea (Lappakangas I) represents the delta-like dilatation in the esker chain. It deposited on a base rising above its surroundings. The bedrock is at a depth of 8 to 12 m below the ground surface. The dominant soil type in the central part of the formation is sand; at the margins it is sand and silt.

Northwards Lappakangas I narrows into a low esker ridge (Lappakangas II) whose total width is 0.1 to 0.2 km; the central coarse part itself is only some tens of metres wide. In the middle of the esker the total thickness of the strata is some 12 m. This central part consists mostly of layers of sorted gravel and sand; at margins the dominant soils are sand and silt.

The northern part of the formation (Lappakangas III) is a flat area where the dominant thickness of the soil strata is 10 to 20 m. It consists mostly of fine sand, being underlain, however, by coarser well-permeable soil types observed during test pumping. The formation is a levelled esker that may have delta-like features.

3.42 Ground-water storage and the flow pattern

Ground-water is stored in practically the entire area of Lappakangas. In the Lappakangas I area the ground-water deposit is 5 to 10 m thick. In the Lappakangas II and III areas the thickness of the stratum saturated by water is 5 to 20 m.

From both the south and the north the ground-water flows in the longitudinal direction of the eskers towards the discharge point in the Lappakangas II area (Fig. 21). Lateral ground-water flow into or from the esker has not been observed. Measured from observation tubes, the ground-water level in the longitudinal section and the hydraulic gradient at different points is given in Fig. 22.

3.43 Investigation results

Observation points for ground-water flow velocity (points 1, 3 and 6) were established on the basis of hydrogeological assessment to represent as well as possible the conditions of the subarea concerned. The aim was to record and interpret the areal variations with a small number of observation tubes. Tube 1 represents the sandy delta area of Lappakangas (Lappakangas I); tube 3 a narrow esker consisting of stony gravel and sand, which is the principal zone of ground-water flow out of the Lappakangas I area. Tube 6 represents the northernmost part of the study area, consisting mainly of fine sand and sand.

The depth dimension of the observation tubes was small owing to the small depth of the layers in the formations. Around tube 3 the soil was so stony and hard to pierce that the tube could not be inserted deeper than 3.5 m below the

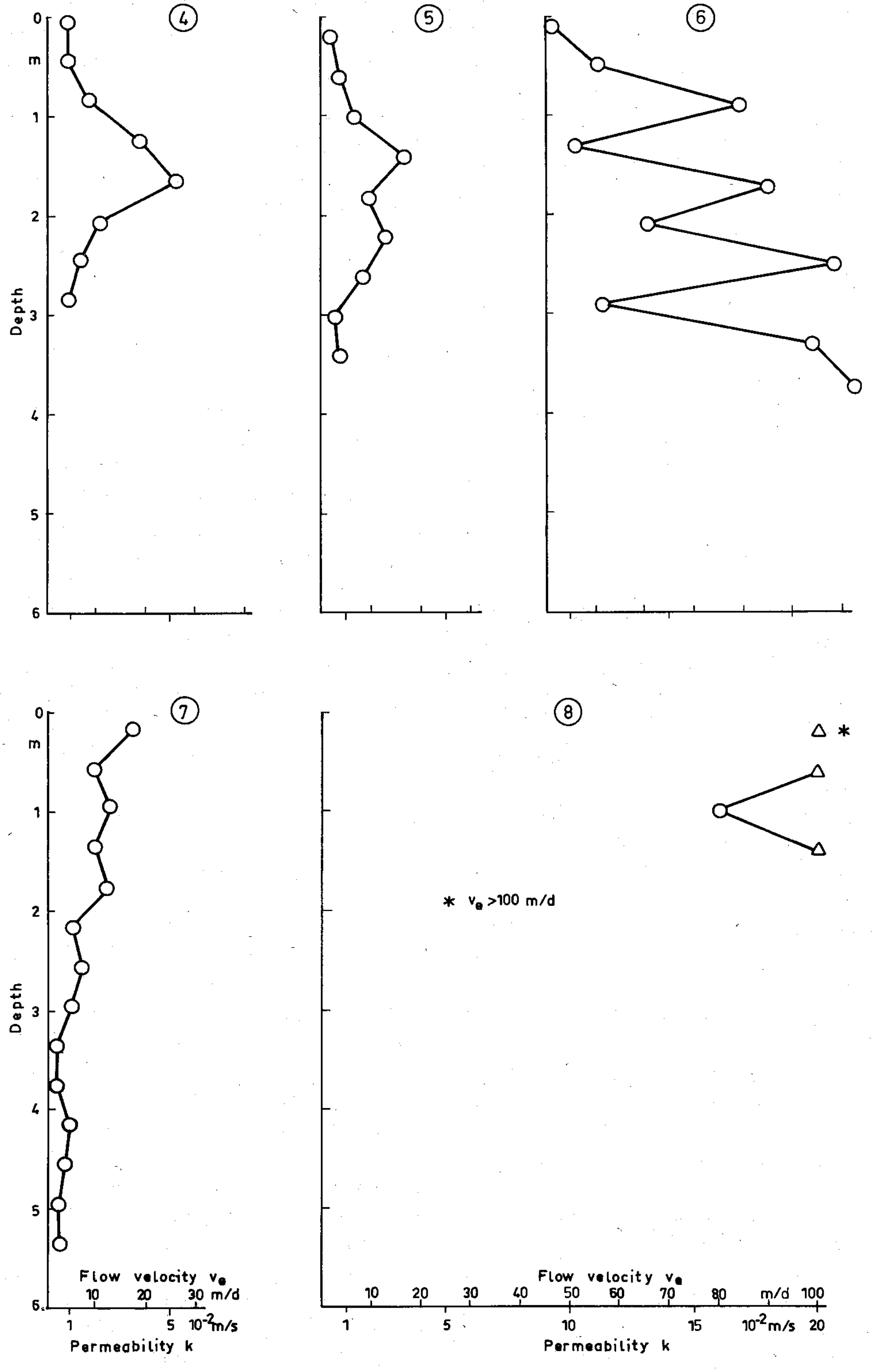

Fig. 20. Ground-water flow velocity and soil permeability at Tullinkangas. 0 m depth = ground-water level.

ground-water level.

Like the other areas mentioned previously, the subareas of Lappakangas I, II and III are discussed with regard to flow velocity and soil permeability even though the number of observations and the representativeness of the results are relatively low.

The total number of flow velocity observations was 39, one of which surpassed the interpretation limit. The greatest flow velocities were observed in area II, where also the permeability was greater than in the other subareas. The next greatest flow velocities were found in area I and the lowest mean velocity in the entire data in area III. Results of flow velocity and permeability are given in Fig. 23.

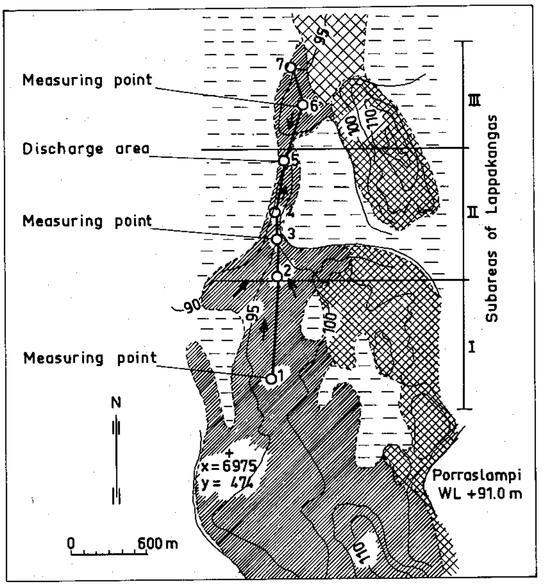

Fig. 21. Hydrogeological map of Lappakangas. Legend, see Fig. 11.

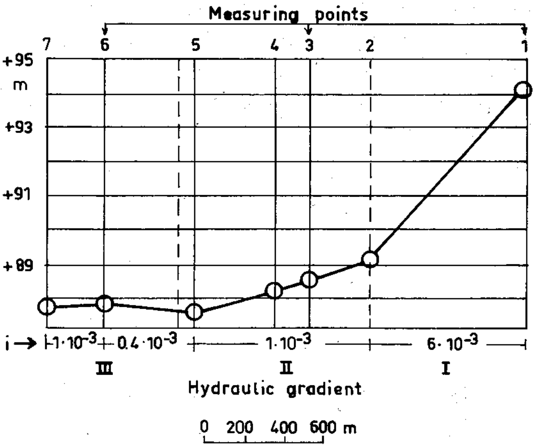

Fig. 22. Longitudinal section of ground-water level at Lappakangas.

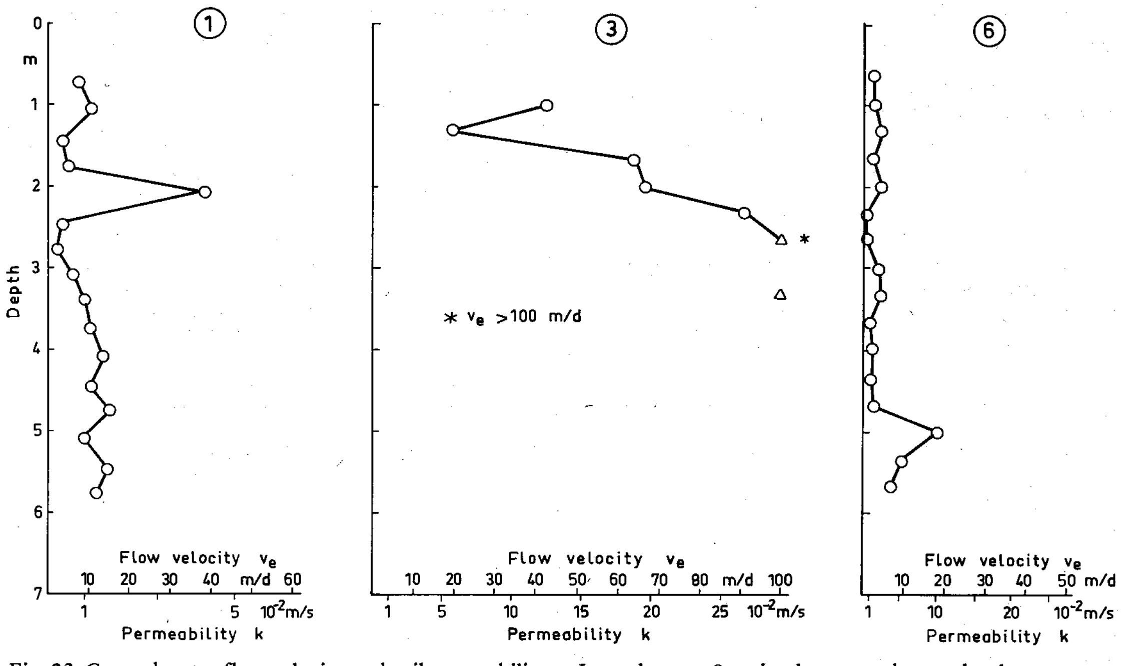

Fig. 23. Ground-water flow velocity and soil permeability at Lappakangas. 0 m depth = ground-water level.

3.5 Observations in the comparison areas

Flow velocity observations in the six comparison areas (Section 2.5, see also Fig. 24) were made by different tracing methods in connection with technical ground-water surveys. These flow velocities were not quite natural. At Hiisimäki and Jälänniemi, where the flow velocity observations were made less than 60 m from the test pumping site, the deviations from the natural velocities were greatest; the observed velocities were estimated to be 2 to 4 times higher than the natural ones. In the other areas the observations were made beyond the immediate vicinity of the pumping site, at a distance of at least 100 m. The velocities were estimated to be 1.5 to 2 times higher than in a natural state. The observations from the comparison areas are given in Table 6.

4. DISCUSSION OF THE RESULTS

4.1 Flow velocity

The observed range of variation in flow velocity was 0.5–>100 m/d. The mean values of the observation results varied in the different areas from 4.3 to 64.1 m/d and the effective flow velocity from 2.9 to 73 m/d. The arithmetic mean of all the observed flow velocities was 22.2 m/d, the mean of the effective velocities in the formations being 13.6 m/d.

The most common flow velocity category with 32 % of the observations, was>2.5–10 m/d. Next came >10–25 m/d, with 25 % of the observations; the other four categories presented in Table 2 comprise 9–13 % of the observations.

Velocities exceeding the interpretation limit (100 m/d) of the observation results were encountered in all four study areas. Thus it was not possible to determine the maximal values of the flow velocity; however, the dilution rates of the tracer observed in the measurements refer to velocities exceeding 200 m/d in the Koskenkorva area. Velocities of the order of 250–300 m/d have been observed over a distance of 1 km in the Gävle esker in Sweden (De Geer 1970, oral communication with Kinsten 1966).

The flow velocity measurements (Fig. 25) show that the ground-water flow velocity varies greatly. Among the esker areas the variation is tenfold but within one esker a hundredfold. The high flow velocities encountered were most common in narrow eskers that, from the point of view of ground-water flow, may be characterized as channel-like (Koskenkorva, Lappakangas II). Low flow velocities were most common in formations with extensive geological strata, e.g. in the delta-like formations of Lappakangas I and III and Tullinkangas.

The ground-water flow velocity observations correlate well with the known geological conditions.

The variation limits of the effective flow velocity of ground-water in the study areas were 2.9–73 m/d and in the comparison areas 2.7–

Table 6. Effective flow velocities, hydraulic gradients and permeability indexes of the comparison areas. Some values from Sweden also given (De Geer 1970).

Area	Flow distance observed m	Effective velocity V_e m/d	Hydraulic gradient 10^{-3}	Permeability index K_e m/s
Kolpene	300	2.7	2	$0.6 \cdot 10^{-2}$
Hanhikemppi	460	9.2	6	$0.7 \cdot 10^{-2}$
Hiisimäki	160	30.0	6	$2.2 \cdot 10^{-2}$
Pässinlukot	120	10.0	1	$4.4 \cdot 10^{-2}$
Jälänniemi	80	60.0	4	$6.6 \cdot 10^{-2}$
Linnamäki	5–15	12.0	0.3	$17.6 \cdot 10^{-2}$
Köping, Sweden	1 200	8 (–10)	2	$1.8 \cdot 10^{-2}$
Eskilstuna, Sweden	500	25	2	$5.5 \cdot 10^{-2}$
Ångermanälven, Sweden		25	2	$5.5 \cdot 10^{-2}$

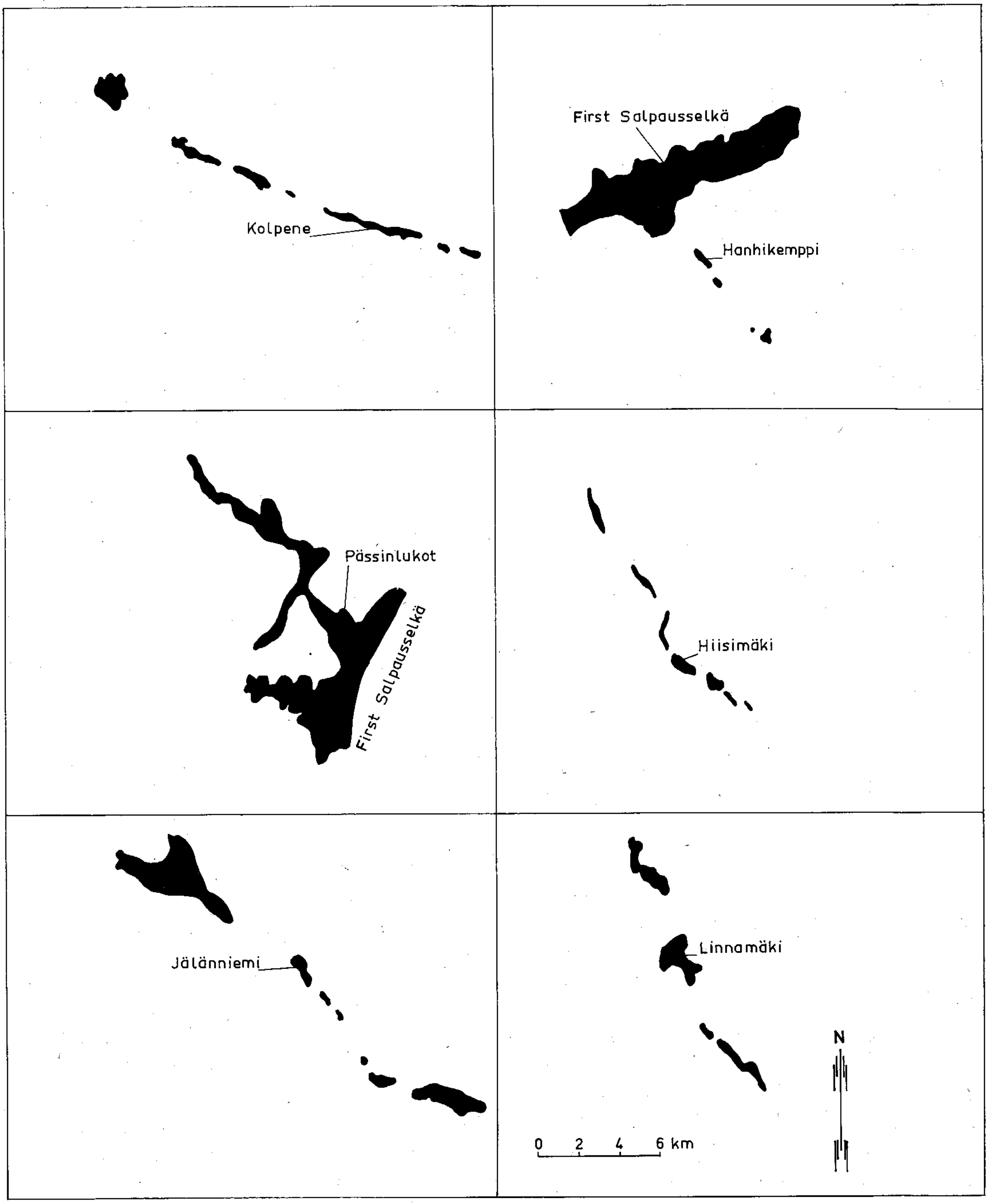

Fig. 24. General maps of the comparison areas.

60 m/d. According to observations made in Sweden (De Geer 1970), the flow velocity observed in the esker at the Köping waterworks was 8—10 m/d, at Eskilstuna 25 m/d and in the esker of Ångermanälv 25 m/d. The observations represent a hydraulic gradient of $2 \cdot 10^{-3}$ which corresponds (in order of magnitude) to the average gradient $1.3 \cdot 10^{-3}$ observed in connection with the present study.

Since ground-water flow velocity varies and is

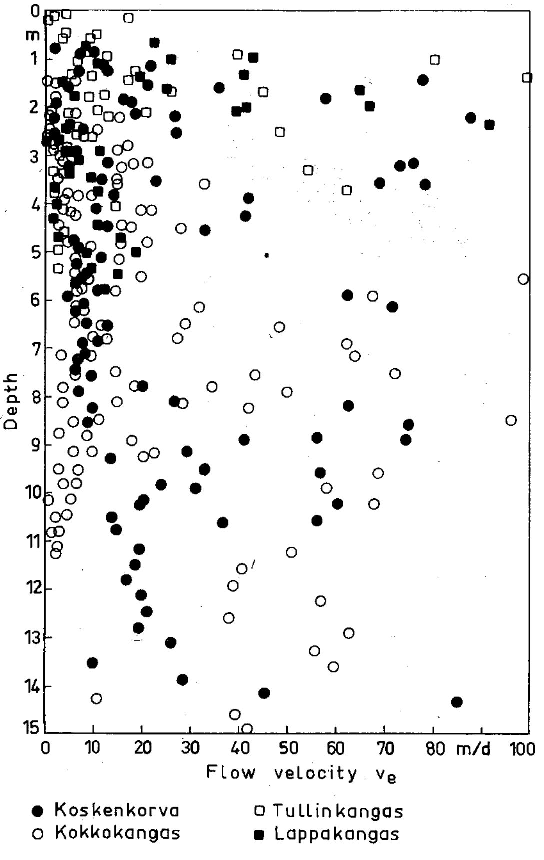

Fig. 25. Combination of interpreted ground-water flow velocities.

influenced by divers factors, it is difficult to compare the flow velocities in the different areas. A better basis for comparison is the permeability index determined with the aid of the movement of water (Section 4.3).

Of the flow velocities in the study areas, 59 % exceeded 10 m/d and 34 % 25 m/d. These, together with the data from the comparison areas and the observations made in Sweden, demonstrate that the flow velocities in the longitudinal direction of eskers may well be more than ten times higher than those indicated by specifications and norms for practical ground-water techniques.

According to the specifications for the protection of ground-waters (Skydd av vattentäkter 1964, Pohjaveden suoja-alueita koskevat ohjeet 1970), the magnitude of ground-water flow velocity for the hydraulic gradient of $5 \cdot 10^{-3}$ is 1 m/d in coarse gravel, 0.5 m/d in fine gravel, 0.25 m/d in coarse sand and 0.1 m/d in fine sand.

Ground-water flow velocity in sand and gravel formations is assessed mainly from information on permeability in various soil fractions. In the relevant text books and manuals (Helenelund 1963, Maarakennusalan tutkimus- ja suunnitteluohjeita 1970, Pohjaveden suoja-alueita koskevat ohjeet 1970, Vesihuolto 1973) the upper permeability limit for gravel is usually given as $1 \cdot 10^{-2}$ m/s. With a soil porosity of 38 % and a hydraulic gradient of $2 \cdot 10^{-3}$, the maximum value of the actual ground-water flow velocity would then be about 4.5 m/d. Only 20 % of the observations in the present study are at or below this value. Thus, the conditions prevailing in eskers require that higher values than those mentioned above should generally be used for flow velocity and permeability in applications of ground-water technique. Hence it is crucial to determine the category of the longitudinal permeability of eskers (Section 4.31).

4.2 Hydraulic gradient

The range of variation in the hydraulic gradient was $0.15 \cdot 10^{-3}$–$6 \cdot 10^{-3}$. The weighted mean value of the different areas varied in the range $0.24 \cdot 10^{-3}$–$6 \cdot 10^{-3}$. The weighted mean of all the observations was $1.3 \cdot 10^{-3}$.

The hydraulic gradient depends, not only on the quantity of water flowing, but also on the permeability of the media. As the recharge of an esker aquifer is limited by the quantity of water originating from precipitation (e.g. von Brömssen 1968, Lemmelä 1976), it seems that it is the permeability of the soil that most significantly regulates the hydraulic gradient in these aquifers. The greater the permeability, the smaller the hydraulic gradient tends to be (see Koskenkorva, Kokkokangas, Tullinkangas at point interval 1–3, Lappakangas II).

In the study areas (with the exception of Lappakangas I and Tullinkangas) the hydraulic gradient, including its variations, represents values typical of narrow eskers. These hydraulic gradients are due, on the one hand, to the permeability of the strata and, on the other, to the ratio of ground-water recharge to the permeable cross-section area. In widespread sand-gravel formations both the permeability and the ratio recharge/permeable cross-section area are unlike those in eskers; thus, the hydraulic gradients are also different.

In all the study areas the hydraulic gradient of ground-water (Figures 12, 15, 19, 22) varies in the longitudinal direction of the formations. In the Koskenkorva area the difference between the observed maximum and minimum values is $0.27 \cdot 10^{-3}$, at Kokkokangas it is $2 \cdot 10^{-3}$, at Tullinkangas (points 1—9) $2.6 \cdot 10^{-3}$ and at Lappakangas (all areas jointly) $5.6 \cdot 10^{-3}$. The range of variation of the gradient in the longitudinal direction of the esker reflects the ground-water flow and the pertinent geological conditions. They are studied in greater detail in Section 5.3.

4.3 Permeability

4.31 Permeability of esker aquifers

The observed range of variation in permeability was $0.1 \cdot 10^{-2}$—$43.9 \cdot 10^{-2}$ m/s. The mean values of the results of the measurements in the different areas varied from $1.2 \cdot 10^{-2}$ to $18.6 \cdot 10^{-2}$ m/s; the range of variation in the permeability index was $0.9 \cdot 10^{-2}$—$21.3 \cdot 10^{-2}$ m/s. The arithmetic mean of all the observations (Fig. 26) was $6 \cdot 10^{-2}$ for the mean permeability and $3.4 \cdot 10^{-2}$ m/s for the permeability index of the formations.

The most common permeability category (Table 5) was $> 1 \cdot 10^{-2}$—$5 \cdot 10^{-2}$ m/s which contained 39 % of the observations. The next greatest category was $> 10 \cdot 10^{-2}$ m/s (28 %). The other three categories contained 9—14 % of the observations.

The highest permeability $43.9 \cdot 10^{-2}$ m/s was observed in the Koskenkorva area. Since, however, higher permeabilities exceeding the interpretation limit of ground-water flow velocity do exist, the maximum values of permeability in the study areas are not known. Nevertheless, the maximum dilution velocities observed in the flow velocity measurements indicate that permeabilities of the order of 1 m/s exist at some measuring points.

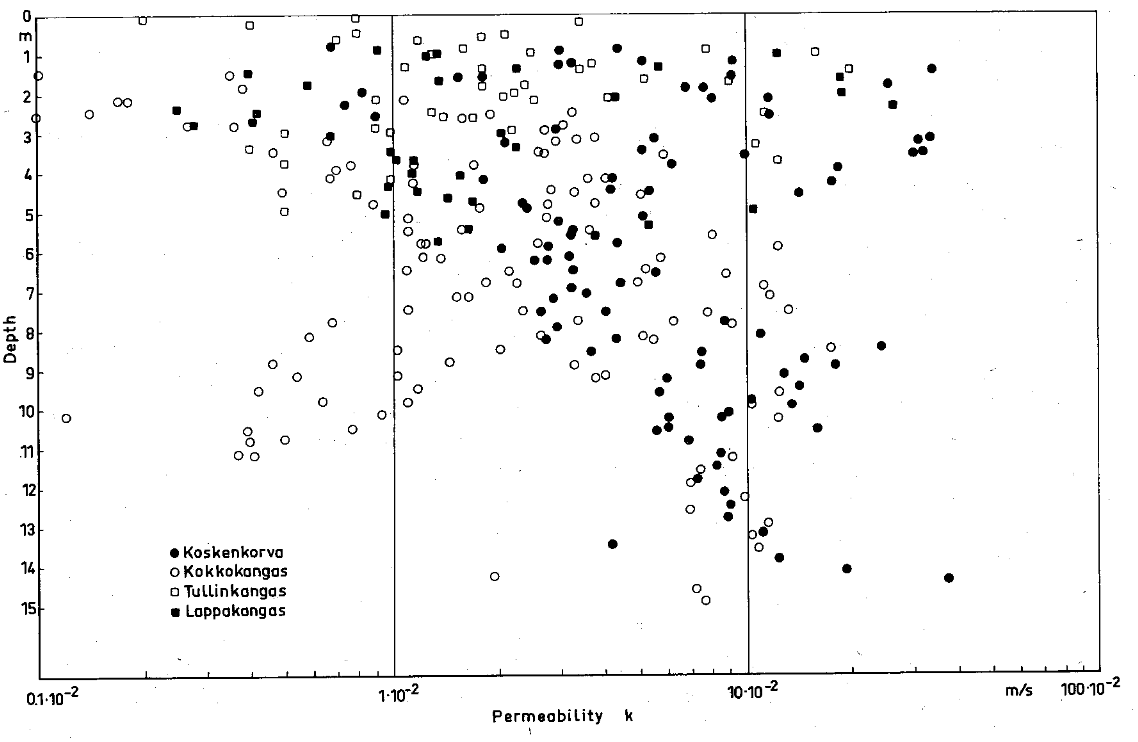

Fig. 26. Combination of interpreted soil permeabilities.

Permeability varies in relation to flow velocity. The high permeabilities in the present data are mainly from Koskenkorva and Lappakangas II; the lowest values are from Lappakangas I and III. Fifty-three per cent of the observations in the study areas fall in permeability category $> 1 \cdot 10^{-2}$–$10 \cdot 10^{-2}$ m/s.

The permeability indexes from the study areas, the comparison areas and some eskers in Sweden are given below from lowest to highest (the names of the study areas are in italics):

	K_e (m/s)
– Kolpene	$0.6 \cdot 10^{-2}$
– Hanhikemppi	$0.7 \cdot 10^{-2}$
– *Lappakangas I*	$0.9 \cdot 10^{-2}$
– *Lappakangas III*	$1.6 \cdot 10^{-2}$
– Köping (Sweden)	$1.8 \cdot 10^{-2}$
– Hiisimäki	$2.2 \cdot 10^{-2}$
– *Tullinkangas*	$2.4 \cdot 10^{-2}$
– *Kokkokangas*	$2.5 \cdot 10^{-2}$
– Pässinlukot	$4.4 \cdot 10^{-2}$
– Eskilstuna (Sweden)	$5.5 \cdot 10^{-2}$
– Ångermanälven (Sweden)	$5.5 \cdot 10^{-2}$
– Jälänniemi	$6.6 \cdot 10^{-2}$
– *Koskenkorva*	$11.9 \cdot 10^{-2}$
– Linnamäki	$17.6 \cdot 10^{-2}$
– *Lappakangas II*	$21.3 \cdot 10^{-2}$

The variation in the permeability index in the study areas is similar to that in the comparison areas. This proves that, in the study areas, the range of variation in permeability and ground-water flow conditions in general is typical of Finnish eskers.

The observation results show that the ground-water flow velocities and the permeabilities of the soil measured by the tracer dilution method are comparable with results obtained by tracing methods.

The permeabilities in the longitudinal direction of eskers are seldom mentioned in the literature. According to Iihola et al. (1977) permeabilities of $0.01 \cdot 10^{-2}$–$0.4 \cdot 10^{-2}$ m/s have been calculated in the Vieremä esker at Forssa. On the basis of test pumping, Airaksinen (1978a) calculated a mean permeability of $0.1 \cdot 10^{-2}$ m/s at Torakangas, Utajärvi commune. According to Kauranne et al. (1972 p. 192), the local maxima of the permeability of the soil are not yet known. In esker formations the k-value may be $10 \cdot 10^{-2}$–$20 \cdot 10^{-2}$ m/s in a limited area.

In the Gävle esker the permeability index would be of the order of 1.4 m/s on the basis of the flow velocity observed in the esker (Section 4.1) and the hydraulic gradient $2 \cdot 10^{-3}$. This shows that the permeability of an esker may be many times higher than the permeabilities given above. The observation is consistent with the local maximum permeabilities established during the present study.

On the basis of observations made during the investigations, the variation in the permeability index of a longitudinal esker aquifer may be presented as follows on the scale $0.1 \cdot 10^{-2}$–$100 \cdot 10^{-2}$ m/s. The different categories in the permeability index are described by attributes which are later used in the text. The figure in brackets is the percentage in each category of the permeability indexes of the 15 eskers.

K_e (m/s)			
$0.1 \cdot 10^{-2}$– $0.5 \cdot 10^{-2}$	very low	-
$>0.5 \cdot 10^{-2}$– $1 \cdot 10^{-2}$	low	(20 %)
$>1 \cdot 10^{-2}$– $5 \cdot 10^{-2}$	medium	(40 %)
$>5 \cdot 10^{-2}$– $10 \cdot 10^{-2}$	high	(20 %)
$>10 \cdot 10^{-2}$– $50 \cdot 10^{-2}$	very high	(20 %)
$>50 \cdot 10^{-2}$– $100 \cdot 10^{-2}$	exceptionally high	-
		100 %

The permeability index of eskers can be used for several purposes, e.g. to study the potential of artificial ground-water recharge. Under normal esker conditions low permeability index ($\leq 1 \cdot 10^{-2}$ m/s) is a sign of good purification capacity; the seepage capacity is, however, then low, usually of the order of only some thousands of cubic metres per day.

The category $>1 \cdot 10^{-2}$–$5 \cdot 10^{-2}$ m/s of the permeability index represents an area suitable for artificial ground-water recharge without pretreatment of raw water. The extreme upper values of the category, however, represent a transitional zone where the pretreatment of water is necessary, especially if poor quality raw water is used or if the quantity of water recharged is high in comparison to the size of the esker.

Formations with a high permeability index

($> 5 \cdot 10^{-2}$ m/s), where the seepage capacity is generally of the order of tens of thousands of cubic metres per day, purify surface water poorly, particularly when they operate at high capacity.

4.32 Comparison of permeability with laboratory determinations

The natural permeability of soil is often simulated in laboratory studies of permeability, depending on the objective of the study. However, as the permeability tests are usually done with compacted samples, the k-values obtained in the laboratory seldom correspond to the permeabilities of the materials in their natural state; the k-values of the latter are generally greater owing to the looseness of the soil. Locally this phenomenon may be very significant depending on the soil structure.

The in situ determinations made in connection with the present study are not easy to compare with laboratory determinations because there are also differences in flow conditions related to the permeability. The flow of water is usually laminar (e.g. Airaksinen 1978b p. 66) under conditions where the in situ measurements have been carried out. In the laboratory determinations, a large hydraulic head is used and turbulent flow is possible; hence, Darcy's law no longer applies.

According to the classification most commonly used in Finland (e.g. Helenelund 1963), the permeability of sand varies in the range $1 \cdot 10^{-4}$–$1 \cdot 10^{-3}$ m/s and that of gravel in the range $1 \cdot 10^{-3}$–$1 \cdot 10^{-2}$ m/s. According to Soveri and Kauranne (1972), the permeability of sand (as soil) varies in the range $1.5 \cdot 10^{-5}$–$4 \cdot 10^{-3}$ and that of gravel in the range $1 \cdot 10^{-3}$–$4 \cdot 10^{-2}$ m/s. Fagerström and Wiesel (1972) give values of $1 \cdot 10^{-4}$–$1 \cdot 10^{-2}$ for medium sand fractions, $1 \cdot 10^{-3}$–$1 \cdot 10^{-1}$ for coarse sand fractions and $1 \cdot 10^{-2}$–1 m/s for fine gravel fractions. The figures are not wholly comparable because sand and gravel as soils or as fractions usually represent different values of permeability.

4.33 Permeability classification of sand and gravel fractions

On the basis of the permeability values presented in Section 4.32 and Table 7 a generalized classification of the permeability of sand-gravel fractions is given (Table 8) that also includes the range of variation in the permeability of soil observed in the present study. As regards grain size, the classification is based on geotechnical soil classification (Korhonen et al. 1974).

According to this permeability classification, the permeability indexes of the formations studied ($0.9 \cdot 10^{-2}$–$21.3 \cdot 10^{-2}$ m/s) correspond to the coarse sand-medium gravel fractions.

Table 7. Permeabilities of different fractions (the author's figure encircled; the others according to Klotz 1969, 1971, 1973).

N:o	Material	Grain size mm	Permeability m/s
1	fine-medium sand	0.1– 0.5	$0.03 \cdot 10^{-2}$
2	coarse sand	0.5– 1.0	$0.2 \cdot 10^{-2}$
3	»	0.5– 1.5	$0.35 \cdot 10^{-2}$
4	»	1 – 2	$0.65 \cdot 10^{-2}$
5	fine gravel	2 – 3	$2.0 \cdot 10^{-2}$
6	»	2 – 3	$2.2 \cdot 10^{-2}$
7	»	2 – 4	$2.4 \cdot 10^{-2}$
8	»	3 – 5	$5.5 \cdot 10^{-2}$
9	»	3 – 6	$16.0 \cdot 10^{-2}$
10	»	4 – 6	$13.5 \cdot 10^{-2}$
11	medium gravel	7 –15	$26.0 \cdot 10^{-2}$
12	medium-coarse gravel	15 –25	$100.0 \cdot 10^{-2}$

5. GEOLOGICAL OBSERVATIONS AND CONCLUSIONS BASED ON GROUND-WATER FLOW

5.1 Aquifers in the study areas

The only criteria in the determination on aquifer composition are the permeability observations. The sorting, compactness and porosity of the soils in the aquifers all interact and hence, the observed permeability does not directly indicate the composition of the soil. Nevertheless, by determining the soil fraction corresponding to the observed permeability, it is possible to infer the composition and type of the soil.

Taking into consideration the grain sizes corresponding to the permeabilities in Table 8 and because the permeability of soil in a natural state is usually higher than it is under laboratory conditions, the aquifers in the study areas can be estimated to consist of the following soils.

permeability k (m/s)	soil	main fractions	
$>10 \cdot 10^{-2}$	gravel	medium gravel	gravel aquifers
$10 \cdot 10^{-2}$– $>5 \cdot 10^{-2}$	sandy gravel	fine gravel	
$5 \cdot 10^{-2}$– $>1 \cdot 10^{-2}$	gravelly sand	fine gravel + coarse sand	sand aquifers
$\lesseqqgtr 1 \cdot 10^{-2}$	sand	coarse + medium sand	

Table 8. General permeability classification of sand and gravel fractions.

Soil fraction subfraction	Grain size mm	Approximate permeability m/s
Sand		
fine sand	0.06– 0.2	$5 \cdot 10^{-6}$–$1 \cdot 10^{-4}$
medium sand	>0.2 – 0.6	$5 \cdot 10^{-5}$–$1 \cdot 10^{-3}$
coarse sand	>0.6 – 2.0	$5 \cdot 10^{-4}$–$1 \cdot 10^{-2}$
Gravel		
fine gravel	>2.0 – 6.0	$5 \cdot 10^{-3}$–$1 \cdot 10^{-1}$
medium gravel	>6.0 –20	$5 \cdot 10^{-2}$–1
coarse gravel	>20 –60	>1

The soil type distribution in the aquifers of three of the areas studied (Koskenkorva, Kokkokangas, Tullinkangas) is given in Fig. 27 and that in percentage of all four study areas separately and combined in Fig. 28.

In the middle of the Koskenkorva esker, from the ground-water level to a depth of 10 m, gravel predominates, reaching to beyond the cross-section studied in the upper part. The ratio gravel/sand aquifers is 71/29≈7/3.

At Kokkokangas gravel occurs in the middle of the cross-section as successive horizons down to a depth of 14 m. Sandy gravel and gravelly sand form intermediate strata. The ratio gravel/sand aquifers is 29/71≈3/7.

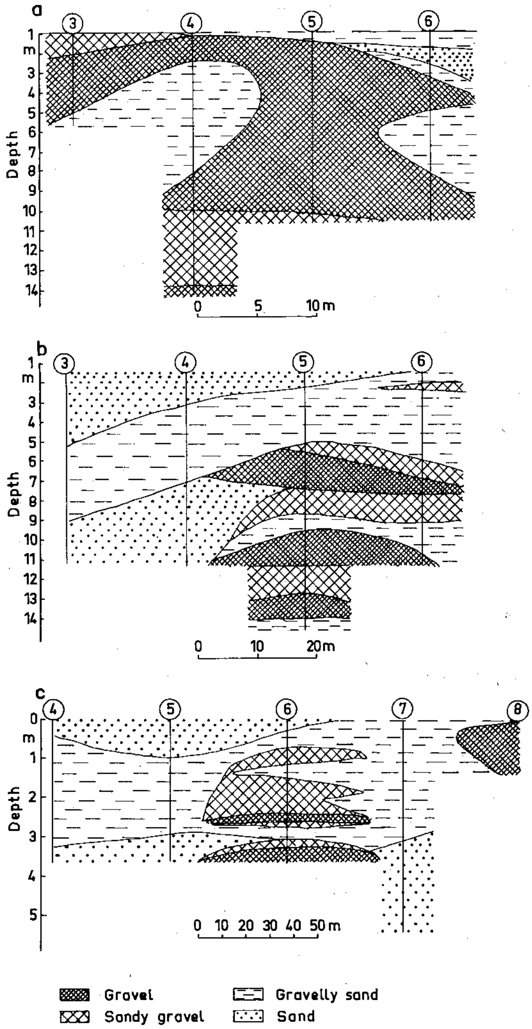

Fig. 27. Aquifer cross-sections at Koskenkorva (a), Kokkokangas (b) and Tullinkangas (c). Encircled numbers = observation points in cross-sections.

At Tullinkangas, at point 6 in the middle of the cross-section, gravel, sandy gravel and gravelly sand aquifers alternate. At point 8, towards the right-hand edge of the section, there is a separate gravel lens. The ratio gravel/sand aquifers is 2.5/7.5.

Lappakangas I consists solely of gravelly sand and sand aquifers, Lappakangas II of gravel aquifers only and Lappakangas III of all four aquifer types. The gravel/sand aquifers ratio is 12/88≈1/9.

A combination of all observations shows that

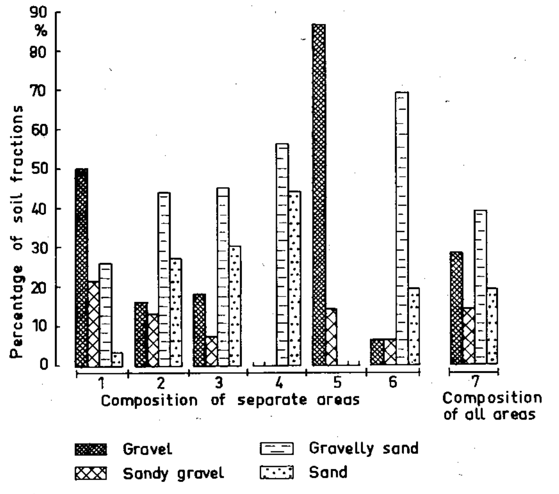

Fig. 28. Composition of soil in the aquifers investigated. 1 = Koskenkorva, 2 = Kokkokangas, 3 = Tullinkangas, 4 = Lappakangas I, 5 = Lappakangas II, 6 = Lappakangas III, 7 = all areas.

the percentage of gravel aquifers is 28, of sandy gravel aquifers 14, of gravelly sand aquifers 39 and of sand aquifers 19. The ratio of gravel/sand aquifers is 42/58≈4/6.

The ratio 4/6 of gravel/sand aquifers in the study areas is roughly double that given for strata above ground-water level by the national gravel and sand resources inventory. According to Niemelä (oral communication 1979), in those strata the estimated ratio of gravel/sand fractions is 2/8.

Whole series of samples taken from the subground-water level in eskers consist almost entirely of gravel. In samples taken from Jäniksenlinna, an esker in Tuusula (southern Finland), 75—90 % of the grains exceeded 2 mm in size. In samples taken from an esker in the Wyborg area 90 % of the grains exceeded 2 mm (Leiviskä 1928). Observations also show the existence of very coarse-grained well sorted strata. Deep-well drilling at Hyvinkää, a town in southern Finland, revealed in the ground-water zone a stratum consisting of pebbles, 5—10 cm in diameter, from which the finer grain sizes were more or less absent (author's observation). V. Okko (1957) has described similar formations in eskers above the ground-water level.

As the permeability of soil usually exceeds $1 \cdot 10^{-2}$ m/s, most of the cross-sections studied are composed of well-sorted material. The strata interpreted as sand and in which permeability is below $1 \cdot 10^{-2}$ m/s may also represent strata with coarse-grained material but poor sorting. These may be formed, for example, in subglacial tunnels, when the entire sediment material is moved by the flow of meltwater and is deposited almost simultaneously; hence little if any sorting can take place (viz. the sliding-bed conditions described by Saunderson 1977; see also Church and Gilbert 1975, Saunderson 1975 and Martini 1977).

5.2 Lateral structure of eskers

Ground-water flow variations indicate that the soil below the ground-water level is stratified in all cross-sections studied. Two main groups can be distinguished on the basis of the variation in the thickness of the layers. All the study areas contain layers 1 to 5 m thick of nearly uniform permeability, called macrostrata in the following (see Figures 13, 16, 20 and 23). They occur at random in the vertical and horizontal directions of the cross-sections studied. Observations indicate that such stratification is most common in horizons whose permeability is below $1 \cdot 10^{-2}$ m/s (Kokkokangas points 3 and 4; Tullinkangas point 7). At Koskenkorva, at points 4 and 6, macrostrata with permeabilities of $1 \cdot 10^{-2}$–$5 \cdot 10^{-2}$ m/s occur (gravelly sand etc.).

Microstrata (thickness < 1 m) occur throughout the cross-sections studied. The majority of them are thinner than the smallest measuring interval used, i.e. 0.3 m. Permeability indicates that the composition varies most in the middle parts of the cross-sections, where highly permeable strata are interlaminated by strata tens of times lower in permeability.

In the cross-sections of Koskenkorva and Kokkokangas subhomogeneous horizons occur that are almost as long as the cross-section is wide. In most of the cross-section areas studied the lateral continuity of the strata is less than one half of the width of the cross-section.

The occurrence of stratification throughout cross-sections studied, though partly as macrostrata, and the slight variations observed in them, is compatible with observations made in hundreds of ground-water investigations on eskers. The variations in the composition of these soil sample series indicates the frequency of both macro- and microstrata in horizons below ground-water level. The thickness and degree of coarseness of the strata vary irregularly. According to Virkkala (1959), this is characteristic of glaciofluvial formations. On the other hand, the macrostrata observed in this study confirm the observation that the core of an esker may be unstratified in places (Repo 1969, Tynni 1969). Further, according to Rust (1975), glaciofluvial formations may show poorly developed stratification and macrostructure characterized by massive gravel deposits. In structure the glaciofluvial formations may be comparable with coarse-grained alluvium, whose sediment structure is difficult to determine (Martini 1977).

5.3 Longitudinal structure of eskers

Observations made on ground-water flow conditions in the study areas indicate the occurrence of long, hydraulically uniform zones, e.g. in the Koskenkorva area where such a flow zone 8 km long has been encountered, and at Kokkokangas, Tullinkangas and Lappakangas, where there are zones about 2 km long. Investigations on eskers in different parts of Finland have revealed even longer, hydraulically coherent zones over 10 km long (e.g. Virttaa-Säkylä esker, southwestern Finland and Isokangas esker, western Finland).

Even in a uniform zone hydraulic conductivity varies in the longitudinal direction of the formation, since the size of the saturated cross-section, the grain size, the degree of sorting and the density of the strata also vary. These influence the hydraulic gradient, whose variation reflects the longitudinal structure of the esker. If the permeable cross-section is constant in the longitudinal direction of the esker, the variation in the hydraulic gradient illustrates the differences in permeability. If permeability is constant in the longitudinal direction of the esker, the variations in the hydraulic gradient usually depict the variations in the area of the cross-section of the formation.

In the Koskenkorva area (over a distance of 2 km north of point 7) the hydraulic gradient and the estimated area of the cross-section of the formation do not vary in order of magnitude. This may prove that, if permeability is used as a criterion, the sediment facies in the basal part of the formation is relatively persistent in a longitudinal direction. The permeability index $11.9 \cdot 10^{-2}$ m/s of the area indicates that the permeability of the soil is very high if the criteria in Section 4.31 are used.

In the Kokkokangas area the estimated cross-sectional area of the formation is of the same order of magnitude between points 2 and 8, whereas the hydraulic gradient grows towards the north-northwest. This indicates enhanced flow resistance in that direction and a gradual change in the soil towards finer grain sizes. The permeability index of the study area, representative of the main section of the formation, is $2.5 \cdot 10^{-2}$ m/s (medium), which is about one fifth of the value at Koskenkorva.

At Tullinkangas the estimated cross-sectional area of the formation is practically unchanged between points 1 and 9, but the hydraulic gradient grows towards the east. The variation in the hydraulic gradient (Fig. 19) indicates that Tullinkangas consists of coarse-grained material between points 1 and 3, from where it is gradually replaced by more fine-grained varieties. The permeability index ($2.4 \cdot 10^{-2}$ m/s) is one fifth of that at Koskenkorva.

At Lappakangas, subareas I, II and III constitute a hydraulically coherent entity. The steep gradient of the ground-water level at Lappakangas I and the permeability index $0.9 \cdot 10^{-2}$ m/s (about one thirteenth of that at Koskenkorva) indicate low permeability in this delta area.

At Lappakangas II permeability attains the maximum value observed in the study areas ($21.3 \cdot 10^{-2}$ m/s; 1.8 times that at Koskenkorva). The zone of high permeability approximately at point 3 and two kilometres north of it indicates the common occurrence of parallel, highly permeable bedding.

The permeability index $1.6 \cdot 10^{-2}$ m/s noted in the studied horizon of Lappakangas III is about one seventh of that at Koskenkorva. This indicates fine-grained soil whose structure is not known in detail.

The present properties of the esker aquifers were formed, not only during primary sedimentation, but also during processes following it. When the strata were deposited in water their structure was partly looser than it is today.

Since their formation, and especially since their emerging from water, they have been affected by other factors, e.g. drying, sinking due to consolidation, collapsing and erosion, etc. all of which have caused changes in the stratification, such as packing, bending, mixing and breaking (McDonald and Shilts 1975, Repo 1969). The topography of the base has also contributed to the deformation. Ground-water flow started in the stratified formations as they emerged from water. Depending on the hydraulic gradient, internal erosion then became possible, especially in the longitudinal direction of the formation.

The longitudinal hydraulic properties of the study areas indicate that hydraulically uniform well-sorted permeable aquifers exist in the core of all of the study areas. The results of the study indicate that the following factors determine the properties of the aquifers.

1. In the basal part of the formations (in the whole vertical section at Tullinkangas) the majority of most permeable strata form nearly horizontal sequences.
2. Diagonal strata, which may occur together with horizontal strata, are not resistant to flow throughout the entire cross-section. In the diagonal layers, the flow of water from one strata to another has cut sufficiently permeable flow channels into them. The same phenomenon may be noted in esker faults or other disruptions in which water breaks its way from one horizon to another.
3. Thick layers deviating markedly in character from and disrupting the main aquifer are absent. Hence, no significant accumulations of poorly sorted or material finer than that in the environment have been observed.

5.4 Genesis of the formations studied

5.41 Koskenkorva

Only small parts of the Koskenkorva esker are visible. An idea of the structure and genesis of the formation is obtained from the form of the esker surface, which is partly covered with postglacial sediments (Fig. 11), and from observations on ground-water movement. The following conclusions were made.

1. In the study area the esker is string-like, narrow and steeply sloped; hence, it was formed between ice walls in a channel or in a subglacial tunnel (c.f. Banerjee and McDonald 1975 p. 135).
2. The formation is hydraulically continuous for 8 km, which proves that, on a large scale at least, the structure is undisturbed. From the very good permeability it can be inferred that the flow velocity of the glacial river was sufficiently high and steady to allow the transportation and sedimentation of gravel and stones. There is no indication of flows and flow variations that would have led to the formation of poorly sorted coarse-grained sediments, e.g. under conditions of the sliding-bed stage. According to Saunderson (1977) the formation of such sediments is characteristic of subglacial tunnels completely filled with water.
3. The cross-sectional structure of the formation, which was further clarified by drilling, shows that the coarse-grained material is in the core of the formation and the fine-grained at the margins. The strata of the esker do not continue in a lateral direction. The preservation of the primary character and the meandering course of the esker (Fig. 11) indicate that it was formed in stagnant ice.
4. The undisturbed structure shows that the glacial river deposited the sediments directly on the bottom of the glacier.

The Koskenkorva esker was probably formed in a subglacial tunnel wholly or partly filled with water. Most of the material was deposited when the tunnel was still less than 40 m wide. In the southernmost part of the esker, beyond the study area, the formation shows delta-like features.

5.42 Kokkokangas

Geological structural features indicate that the northern part of the level-surfaced Kokkokangas formation is an esker characterized by sorting, stratification, longitudinal continuity of the strata and grain-sizes ranging from sand to gravel. The esker was formed in a channel less than 0.1 km wide near the margin of the ice, where the flow velocities of the glacial river represented average glacier conditions. There were no exceptionally great flow velocity variations, which is indicated by the regularity of the grain size and the absence of coarser stony fractions and finer silty ones. The southern part of Kokkokangas, a contemporaneous delta-like extension of the former, is beyond the scope of this study.

5.43 Tullinkangas

Geological development during the initial phase of Tullinkangas is divided into two parts: first a narrow, steep-sided poorly sorted esker was formed; later this was covered by a delta that developed from east to west. According to M. Okko (1972), the Tullinkangas area was bordered by a belt of broken-up stagnant ice, where Tullinkangas constituted a marginal delta.

The present study shows that at the genesis of the core of the delta, the meltwater flowed at high velocity, since for 4/5 of its length from the proximal end the delta contains a uniform sequence of highly permeable strata. Towards the distal end the grain size gradually diminishes, which is indicated by the increase in flow resistance reflected by the hydraulic gradient.

Meltwater flow and the formation of the esker-delta complex in the Tullinkangas area can be described as follows.

1. Flow of the river in a narrow subglacial tunnel in the western and southern parts of Tullinkangas and the transportation of material probably under sliding-bed conditions.
2. The break-through of the tunnel at the Lake Selkäjärvi into a glacial bay and the discharge into the bay of the bulk of the flow. The almost simultaneous sedimentation of the material transported by the glacial river in the tunnel section south of the bay; the delta begins to form.
3. Formation of the delta of Tullinkangas; first, for 4/5 of its length from the proximal end, narrower than at the distal end; later of equal width and extending as far as the esker formed earlier at the southern side.

5.44 Lappakangas

After a disruption in the esker chain (Fig. 10) large-scale sedimentation took place. The main factor in this was probably the great variation in the topography of the base, especially the elevated, convex bedrock surface at Lappakangas. This caused the locally thinner ice to break under the effect of a subglacial water flow that formed a dilatation or bay in the glacial river.

The subglacial tunnel running from north to south, and which was only some ten metres wide, formed diverse glaciofluvial strata.

The southernmost part of Lappakangas, which is beyond the scope of this study, contains appreciable coarse-grained but poorly sorted material.

Geological development continued under the delta conditions of Lappakangas I, where well-sorted, mainly sandy deposits formed in the space opened up at mouth of the glacial river.

In the glacial river itself (Lappakangas II) the flow, most probably in a tunnel entirely filled with water, was very strong at first causing deposition of highly permeable material on the bottom. At a later stage the tunnel become a channel and – with diminishing flow velocity – the topmost sand-predominant strata were formed (partly Lappakangas II, Lappakangas III).

5.5 Discussion

The occurrence of continuous sequences of strata several kilometres long is a characteristic feature of the basal part of eskers and reflects their genetic conditions. It is difficult to imagine that these strata were formed as a series of successive accumulations; they were probably formed more or less simultaneously in a facies relatively persistent in a longitudinal direction.

A basal facies like this, characterized by (1) good sorting, (2) coarse grain size and (3) sediment structure of long horizontal sequences, most probably formed during the early glaciofluvial stage. The basic requirement for its formation is stagnant ice conditions. The formation of a basal facies is probably affected, not only by the high flow velocity of water but also by the rudimental drainage system, which causes relatively little lateral transport of sediments into the main flow artery and good sorting.

In these conditions, deposition also in completely water-filled tunnels seems possible (c.f. Saunderson 1975, 1977, Banerjee and McDonald 1975).

Eskers form, not only at the margins of glaciers, but also several kilometres within the glacier. Banerjee and McDonald (1975) give a distance of 3 to 4 kilometres.

The character of the basal structure of eskers described in this study indicates that sedimentation is possible in a subglacial tunnel as far from the glacier margin as is indicated by the length of hydraulically uniform strata; this may be as much as ten kilometres or more.

Eskers commonly form deep inside glacier; as is indirectly shown by long eskers without delta-like dilatations (ref. also Saunderson 1977 p. 635). In the formation of many esker chains all material coarser than silt deposited in or at the margins of esker ridges; hence delta formation is not visible.

The possibility of sedimentation far from the glacier margin is also indicated by observations of an extensive area of broken-up stagnant ice in the marginal belt of the glacier. M. Okko (1972) has described such a belt in the environment of Tullinkangas, that was 8 km wide.

SUMMARY

The study dealt with ground-water flow velocity and the relevant hydraulic gradient, the permeability of soil in the longitudinal direction of eskers and, on the basis of water movements, the internal structure of eskers. A total of 314 flow velocity measurements were made in four study areas by the tracer dilution method and using an interpretation model that takes hydraulic disturbances into account. Both method and model were developed in connection with this work. Permeability was calculated from flow velocity observations. The results were compared with those obtained from studies of water movement in six other esker areas. The following are the main findings and conclusions:

1. The tracer dilution method makes it possible to study both ground-water flow velocity and the permeability of soil and, by a combination of these and related results, the aquifer properties and geological structures of these formations.
2. The actual ground-water flow velocity varied within the limits 0.5–>100 m/d. In different formations the effective flow velocity varied in the range 2.9–73 m/d, the mean value being 13.6 m/d. Thirty-two per cent of the observations fell in the flow velocity category >2.5–10 m/d, and twenty-five in the category >10–25 m/d.
3. The range of variation for the hydraulic gradient was $0.15 \cdot 10^{-3}$–$6 \cdot 10^{-3}$. The weighted mean of all the observations was $1.3 \cdot 10^{-3}$.
4. The permeability of the soil varied in the range $0.1 \cdot 10^{-2}$–$43.9 \cdot 10^{-2}$ m/s. The results show that the longitudinal permeability of eskers may even be a multiple of the permeabilities generally cited, e.g. in specifications for practical ground-water techniques. In the context of this study the concept of the permeability index of a formation was developed to depict the effective permeability of that formation. The permeability index varied in the range $0.9 \cdot 10^{-2}$–$21.3 \cdot 10^{-2}$ m/s, the mean value being $3.4 \cdot 10^{-2}$ m/s. The most common permeability category was $>1 \cdot 10^{-2}$–$5 \cdot 10^{-2}$ m/s (39 %); the following was the category $>10 \cdot 10^{-2}$ m/s (28 %). The conditions in the study areas and in the comparison areas were examined on the basis of the permeability index of the formation. The total variation of the index was in the range $0.6 \cdot 10^{-2}$–$21.3 \cdot 10^{-2}$ m/s. The permeability index in the longitudinal direction of the eskers varies generally within the limits $0.1 \cdot 10^{-2}$–1 m/s.

The permeability index of the eskers is applicable, for example, in studies on the feasibility of artificial ground-water recharge. A high permeability index indicates good seepage but poor purification capacity; a low permeability index indicates the reverse.

A permeability classification for sand and gravel fractions was drawn up in the course of this study. It covers the fractions from fine sand to coarse gravel ($k = 5 \cdot 10^{-6}$–>1 m/s).

5. The principal aquifers are gravel and sand in various ratios. The ratio of gravel to sand aquifers in the ground-water zones of the study areas was estimated to be 4/6.
6. Measurements show that, in most parts of the study areas, the stratification is small in scale. Macrostrata (thickness 1–5 m) occur mostly in horizons where permeability is less than $1 \cdot 10^{-2}$ m/s.
7. In the study areas hydraulically continuous strata attain a length of 2–8 km. Similar zones, over 10 km in length, have been observed in Finnish eskers. Thus, the prosess of esker formation creates long, highly permeable and mainly horizontal sequences of strata in the basal parts of eskers. The possible diagonal strata cause no remarkable flow resistance. In the basal parts of the eskers studied the material is well sorted; large, poorly sorted accumulations are absent.
8. The undisturbed highly permeable structure and the meandering course of eskers show that they formed in glacier rivers flowing within the stagnant ice.
9. Longitudinal permeability shows that the basal parts of many narrow eskers stratified subglacially during the early glaciofluvial phase. The stratification often took place from the bottom upwards in long and relatively persistent facies. Thus, stratification was often a more or less concurrent event in a reach of certain length. The sedimentation process of the early glaciofluvial phase was probably different from the sedimentation process in the later phase owing to differences in flow velocity, the size of the drainage system and the amount of sediment material. Poorly sorted strata that may represent sliding-bed conditions have been observed in one part of the Tullinkangas area only.
10. On the basis of the uniform longitudinal structure of the eskers and assuming stagnant ice conditions it seems likely that the stratification of glaciofluvial material in the basal parts of the eskers can take place deep within a glacier. The distance from the margin of the glacier to the extreme stratification area may be of the same order as the length of the longest hydraulically uniform sequences, i.e. over 10 km. This assumption is indirectly also supported by observations on long string-like esker chains devoid of deltas and on wide belts of broken-up stagnant ice.

Observations show that the structures and other properties of eskers can be studied with the aid of water movement and the relevant parameters more effectively than by many other methods. All the parameters in Darcy's law: flow velocity, hydraulic gradient and permeability of the media, either alone or together, are then applicable, but it requires knowledge of the geological setting and its interpretation.

ACKNOWLEDGEMENTS

I express my warmest thanks to Professor Kauko Korpela of the University of Turku, later of the Geological Survey of Finland, for his inspiring guidance and criticism in the course of my work.

I am deeply indebted to Professor Seppo Mustonen of the Water Research Institute of the National Board of Waters, who accepted the subject of my research as part of the Institute's scientific programme and who, in both word and deed, gave me the encouragement to bring the work to its conclusion.

My gratitude is further due to many of my colleagues, particularly Professor Kalevi Kauranne, Dr. Pertti Lahermo and Dr. Jouko Niemelä, who read the manuscript and were always ready with valuable advice and constructive criticism, and Professor Kalevi Virkkala, who suggested ways of arranging the data.

Of the numerous persons who participated in the work I should like to make special mention of Mr. Lauri Aarre for his significant contribution to the development of the measuring instrument; later also Mr. Heikki Wihuri took part in this work, Mr. Tapani Turja, who carried out the field measurements, Mr. Jorma Määttänen, who participated in field and laboratory investigations, Mr. Pekka Turtiainen for the important part he played in developing the interpretation model, and Mr. Aarne Keko, who was of great assistance during the field investigations in Kokkokangas.

Mr. Heikki Rinta-Jyllilä, Mrs. Elina Toivonen, Mrs. Riitta Määränen and Mrs. Pirkko Laakso participated in the handling of the data and in the draftsmanship. Mrs. Terttu Halme and Mrs. Sirkka Vuoristo examined the figures in their final form. Mrs. Marja Jokinen and Miss Tuula Turunen helped with the typing. The final typing was made by Miss Tuula Matilainen and layout by Mrs. Raili Malinen.

The manuscript was translated into English by Miss Tarja Pyykkö. The final English revision was done by Mrs. Gillian Häkli.

In bringing the study to its conclusion the financial support I received in various forms from my present employer the National Board of Waters (General Planning Division) was of foremost importance. Financial support was also obtained from the Fund for the Advancement of Technology, Special Fund of Soil and Water Ltd. (Tekniikan Edistämissäätiö, Maa ja Vesi Oy:n Erikoisrahasto) and from the Academy of Finland.

Vantaa, April 1979

Esko Mälkki

LOPPUTIIVISTELMÄ

Tutkimuksessa selvitettiin pitkittäisharjujen pohjaveden virtausnopeutta ja tähän liittyvää hydraulista gradienttia, maaperän vedenläpäisevyyttä sekä veden liikkeeseen perustuen harjujen juuriosien rakennetta. Neljällä tutkimusalueella tehtiin 314 virtausnopeusmittausta tässä työssä kehitettyä tracer dilution -mittausmenetelmää ja hydrauliset häiriötekijät huomioon ottavaa tulostulkintaa käyttäen. Vedenläpäisevyydet määritettiin virtausnopeushavaintojen perusteella laskennollisesti. Tuloksia verrattiin muilla harjualueilla (6 kpl) merkkiainetutkimuksilla saatuihin tuloksiin. Seuraavassa esitetään keskeiset havainnot ja päätelmät.

1. Tracer dilution -mittausmenetelmällä voidaan tutkia sekä pohjaveden virtausnopeutta että maaperän vedenläpäisevyyttä ja mitattuja parametreja hyväksikäyttäen muodostumien akviferiominaisuuksia ja geologisia rakenteita.
2. Pohjaveden todellinen virtausnopeus vaihteli rajoissa 0,5–>100 m/d. Eri muodostumissa tehollinen virtausnopeus vaihteli rajoissa 2,9–73 m/d näiden keskiarvon ollessa 13,6 m/d. 32 % havainnoista oli virtausnopeusluokassa >2,5–10 m/d ja 25 % havainnoista luokassa >10–25 m/d.
3. Hydraulisen gradientin vaihtelurajat olivat $0{,}15\cdot10^{-3}$–$6\cdot10^{-3}$. Kaikkien havaintojen painollinen keskiarvo oli $1{,}3\cdot10^{-3}$.
4. Vedenläpäisevyyden vaihtelurajat olivat $0{,}1\cdot10^{-2}$–$43{,}9\cdot10^{-2}$ m/s. Tutkimustulokset osoittavat, että harjujen pituussuuntainen vedenläpäisevyys on jopa kertaluokkaa suurempi, kuin mitä esimerkiksi käytännön pohjavesitekniikkaan liittyvissä ohjeissa yleisesti esitetään. Työssä kehitetty käsite vedenläpäisevyysluku, mikä kuvaa muodostuman tehollista läpäisevyyttä, vaihteli rajoissa $0{,}9\cdot10^{-2}$–$21{,}3\cdot10^{-2}$ m/s keskiarvon ollessa $3{,}4\cdot10^{-2}$ m/s. Yleisin vedenläpäisevyysluokka oli $>1\cdot10^{-2}$–$5\cdot10^{-2}$ m/s (39 %). Seuraavaksi yleisin oli luokka $>10\cdot10^{-2}$ m/s (28 %). Tutkimus- ja vertailualueiden olosuhteita tarkasteltiin muodostuman vedenläpäisevyyslukua käyttäen. Tämä vaihteli kokonaisuutena rajoissa $0{,}6\cdot10^{-2}$–$21{,}3\cdot10^{-2}$ m/s. Harjujen pituussuunnan vedenläpäisevyysluku vaihtelee kokonaisuutena rajoissa $0{,}1\cdot10^{-2}$–1 m/s.

   Harjujen pituussuunnan vedenläpäisevyyslukua voidaan käyttää hyväksi mm. tutkittaessa tekopohjaveden käyttöedellytyksiä. Suuri vedenläpäisevyysluku harjussa osoittaa suurta suotovirtauskapasiteettia mutta vastaavasti pientä raakaveden puhdistuskykyä, pieni vedenläpäisevyysluku päinvastoin.

   Työn yhteydessä laadittiin yleisluontoinen hiekka- ja soralajitteiden vedenläpäisevyysluokitus. Se ulottuu hienohiekka-lajitteesta karkeasora-lajitteeseen ($k=5\cdot10^{-6}$–>1 m/s).
5. Pääakvifereina ovat hiekka ja sora eri suhteissa. Arvion mukaan sora- ja hiekka-akvifereiden suhde tutkimusalueiden pohjavesivyöhykkeissä on noin 4/6.
6. Mittaustulokset osoittavat poikkileikkauksien läpi ulottuvaa, valtaosaltaan pienipiirteistä kerrosrakennetta. Vedenläpäisevyydeltään alle $1\cdot10^{-2}$ m/s olevissa horisonteissa esiintyy eniten suurkerroksellisuutta (kerrospaksuus 1–5 m).
7. Hydraulisesti hyvän yhteyden omaavat kerrostumat ovat tutkimusalueilla pituudeltaan 2–8 km. Suomen harjuissa on havaintoja jopa yli 10 km pituisista hydraulisesti yhtenäisistä

vyöhykkeistä. Pitkittäisharjujen muodostumisprosessi tuottaa siten harjujen juuriosiin pitkiä, hyvin läpäiseviä, pääosaltaan horisontaalisia kerrossarjoja. Mahdollinen diagonaalikerrostumien vaikutus ei tule virtausvastuksena näkyviin. Todennäköisesti pohjavesivirtaus on raivannut johteita diagonaalisten heikosti läpäisevien kerrosten läpi. Tutkittujen harjujen juuriosissa ei esiinny suuria huonosti lajittuneita kerroksia tai kasaumia, vaan aines on kokonaisuutena hyvin lajittunutta.

8. Muodostumien häiriintymätön, hyvin vettäjohtava rakenne samoinkuin harjujen monesti mutkaileva, meanderimainen kulku osoittavat kerrostumisen tapahtuneen kuolleeseen jäähän.
9. Pituussuuntaisen läpäisevyyden perusteella arvioidaan, että erityisesti kapeiden harjujen juuriosat ovat kerrostuneet subglasiaalisesti jo varhaisessa jäätikköjokivaiheessa. Kerrostuminen on usein tapahtunut pohjalta lähtien pitkinä, horisontaalisuunnassa yhtenäisinä sarjoina — määrätyn pituisessa jaksossa enemmän tai vähemmän samanaikaisesti. Todennäköisesti harjujen juuriosien sedimentaatioprosessi poikkeaa myöhemmän jäätikköjokivaiheen aikaisesta, johtuen mm. aikaisen jäätikköjokivaiheen erilaisista virtausnopeuksista, vielä huonosti kehittyneistä jäätikköjoen sivuuomista ja tulevan sedimenttimateriaalin määrästä.

   Huonosti lajittuneita kerrostumia, kuten sliding-bed -vaiheen olosuhteissa muodostuneita, on havaittu vain Tullinkankaan yhdessä osassa.
10. Harjujen pituussuuntaisen yhtenäisen rakenteen perusteella sekä olettaen kuolleen jään olosuhteita pidetään mahdollisena, että glasifluviaalisen aineksen kerrostumista harjujen juuriosiin tapahtuu syvällä jäätikön sisällä. Ulottuvuus jäätikön reunasta kerrostumisalueille voi olla samaa suuruusluokkaa kuin pisimmät hydraulisesti yhtenäiset kerrossarjat — jopa kertaluokkaa yli 10 km. Tällaisen kerrostumisetäisyyden mahdollisuuteen viittaavat epäsuorasti myös havainnot pitkistä nauhamaisista harjujaksoista vailla deltoja sekä havainnot leveistä, paloittuneista kuolleen jään vyöhykkeistä.

Tutkimushavainnot osoittavat, että veden liiketilailmiöiden hyväksikäyttö antaa mahdollisuuksia tutkia toistaiseksi vielä vähän tunnettua glasifluviaalisten muodostumien pohjaosien rakennetta useita muita menetelmiä tehokkaammin. Kaikki Darcyn lain mukaiset parametrit: pohjaveden virtausnopeus, väliaineen vedenläpäisevyys sekä hydraulinen gradientti antavat käyttökelpoista tietoa edellyttäen kuitenkin aina geologisten ympäristöolosuhteiden tulkintaa.

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